11th

Global Conference on Sustainable Manufacturing

Innovative Solutions

Berlin, Germany, 23rd – 25th September, 2013

GCSM

Proceedings

Günther Seliger
Editor

Sponsored by the International Academy for Production Engineering (CIRP)
Berlin Institute of Technology, Berlin, Germany
Collaborative Research Centre 1026

11th Global Conference on Sustainable Manufacturing
Sponsored by the International Academy for Production Engineering (CIRP)

Proceedings

11th Global Conference on Sustainable Manufacturing

Innovative Solutions

Berlin, Germany
23rd–25th September, 2013

Günther Seliger
Editor

Technische Universität Berlin
Institute of Machine Tools and Factory Management
Fraunhofer IPK
Global Production Engineering
CRC 1026: Sustainable Manufacturing – Shaping Global Value Creation
Sponsored by the German National Science Foundation (DFG)

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.dnb.de.

Editor
Günther Seliger
Technische Universität Berlin, Germany
Department of Machine Tools and Factory Management
Pascalstr. 8–9, 10587 Berlin
Germany
seliger@mf.tu-berlin.de

Universitätsverlag der TU Berlin 2013
http://www.univerlag.tu-berlin.de

Fasanenstr. 88, 10623 Berlin
Tel.: +49 (0)30 314 76131 / Fax: -76133
E-Mail: publikationen@ub.tu-berlin.de

ISBN 978-3-7983-2609-5 (online)

Online published on the Digital Repository of the Technische Universität Berlin:
URL http://opus4.kobv.de/opus4-tuberlin/frontdoor/index/index/docId/4027
URN urn:nbn:de:kobv:83-opus4-40276
http://nbn-resolving.de/urn:nbn:de:kobv:83-opus4-40276

Table of Contents

Session 3: Resource Utilization

Session 4: Equipment

Session 5: Knowledge

Session 6: Lifecycle

Session 7: Maintenance

Session 8: Process

Session 9: Implementations

Session 10: Remanufacturing

Session 11: Energy Efficiency

Session 12: Material

Session 13: Design

Session 14: Supply Chain

Session 15: Energy Assessment

Session 16: Sustainability Assessment

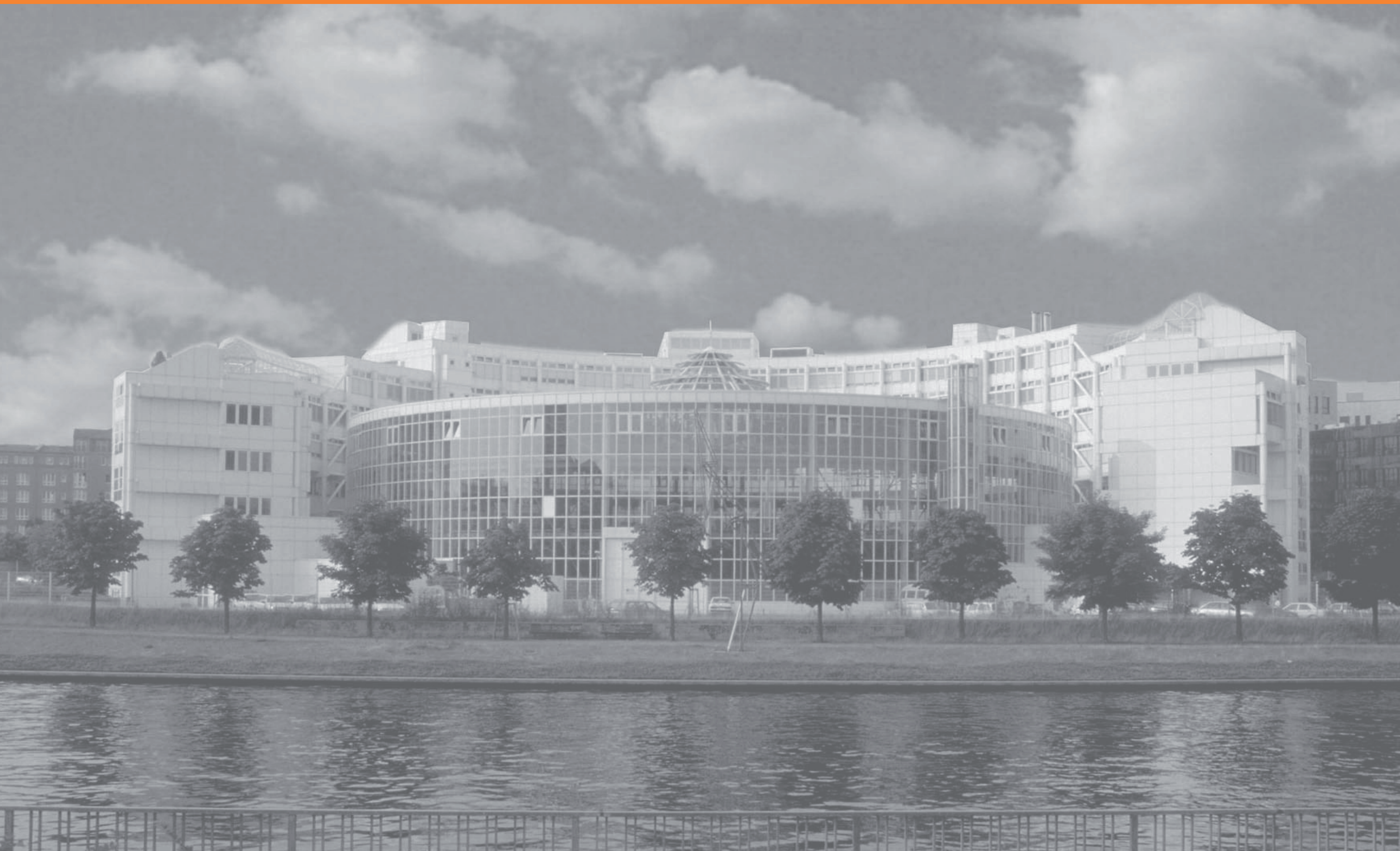
Session 17: Strategies

Session 18: Tools and Technologies

Session 19: Energy Awareness

List of Authors

Keynotes



GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany
CIRP

Chinese approaches to sustainable manufacturing

Ö. S. Ganiyusufoglu
Shenyang Machine Tool (Group) Co., Ltd.

Abstract
The balance of global economic power is shifting. Traditionally strong countries are stagnating and a new corps of hopefuls is waiting in the wings. These emerging countries are characterized by largely untapped natural resources and a wealth of latent human talent. At the same time, internet penetration and the revolution in speed of communication has laid the foundation for a new type of Industrial Revolution with sustainable manufacturing at its heart. China is at the forefront of this new group with a number of industries well-positioned to step forward onto the global stage. This paper discusses the current status and strategic plans of Shenyang Machine Tool, the largest machine tool manufacturer in the world. Sustainable manufacturing is only just entering the consciousness of the global machine tool industry. There is not only tremendous capacity for the implementation of sustainable manufacturing principles, the very future of the industry depends on them.
Keywords:
China, Co-operations, Machine Tools, SMART, Sustainable Manufacturing

1 INTRODUCTION

The global economic balance is undergoing dramatic change. The mature, industrialized countries are stagnating; their pace of development slowing. Protecting their competitive positions is becoming harder and harder. Rather than set new standards, individuals are challenged just to maintain the existing ones. Decreasing resources and increasing energy demands are creating higher costs not only for manufacturing goods but also in our daily lives.

Meanwhile, some emerging countries are attracting more and more global attention. Their largely untapped potential for development, both in terms of human capital and natural resources, grants them an important position on the global stage. In particular the BRICS countries, comprising Brazil, China, India, Russia and South Africa, are fast becoming essential players in the global economy.

Regardless of development level, the advent of new technology and the rise of social media have made global communication at incredible speed a reality for all. This will have an important impact on future global development. Already, the current phase has been named Industry 4.0 – as in the 4th Industrial Revolution.

The aforementioned developments combined with the rise of sustainable manufacturing processes will lead to new products in all areas of life as well as to new ideas for manufacturing itself and the business environment

This presentation examines the Chinese approach to sustainable manufacturing via the example of the country`s leading machine tool manufacturer. As machine tools are “mother machines” for any product in the word, the aforementioned conditions will have a critical impact on the development of new machine tools. Furthermore, as mother machines their advancement will induce great changes across the world.

2 INTRODUCING SHENYANG MACHINE TOOL

Despite tracing its roots back to the late 1930s, the Chinese machine tool industry was a relatively late entrant to the world stage. Post-reform and opening up, as China’s economy gained steam and began to record decades of unparalleled growth, the domestic machine tool industry also underwent tremendous expansion.

Shenyang Machine Tool Group (SYMG) was founded in 1995 through consolidation of the three largest machine tool works in Shenyang, China’s historical manufacturing heart and the capital of Liaoning province.

Ranked 36th globally by revenue in 2002, SYMG by 2011 not only stood at the forefront of China’s machine tool manufacturers but had become the world’s largest machine tool manufacturer with revenues in excess of €1.8 billion.

With aggressively-funded strategic R&D centers in Berlin, Shanghai, and Beijing and a global workforce of 18,000 highly skilled workers, SYMG is uniquely positioned to capitalize on the coming industrial transformation.

3 INDUSTRY DEVELOPMENT MILESTONES

With equipment operation an entirely manual affair, in its infancy machining revolved around the development and maintenance of a highly skilled workforce. Apprenticeships were common and peak worker productivity was only realized after years of gradual training and study.

The first big breakthrough was the advent of ‘numerical control’ (NC) in the early 1940s. Existing manual machining equipment was retrofit with crude motor-driven mechanical assemblies that accepted punched tape to control workpiece location, cutting speed and depth. In a stroke, one expert machinist could record his sequence of actions and

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

propagate them via punch tape across entire factories. The impact on production efficiency was staggering.

As the 1960s wore on and the computer revolution took hold the next great breakthrough was the arrival of ‘computerized numerical control’ (CNC). A natural successor to NC systems, CNC was the end of the traditional machinist as the industry had known him for decades. In his place now stood a highly skilled designer who programmed the machines and a team of relatively lower skilled operators which oversaw the loading, activation, and unloading of individual machine tools. This arrangement lead to another leap forwards in productivity and also dramatically increased the flexibility, as machining programs could be easily and quickly modified as needs required.

From the 1980s onward the manufacturing industry continued to experience technical breakthroughs: cutting speeds rapidly increased, automation and robotics went from high concept to baseline technology, and hybrid CNC platforms capable of performing a variety of cuttings tasks including turning, milling, tapping, laser cutting and so on rose to prominence.

Despite this continuous technological progress, the actual productivity, efficiency, and flexibility gains generated at each step of development have been diminishing for some time. Core technologies have standardized across manufacturers, deep research and design spending is yielding fewer and fewer returns, and the pace of development has begun to stagnate.

Current cutting-edge research is concerned with maximizing the efficiency of energy usage and raw materials, and creating more environmentally-friendly products. These motivations, honorable though they be, are meaningful only for the uppermost reaches of the manufacturing industry. Reducing electrical consumption by 2%, for example, is of relatively little consequence to the manufacturing industry’s mid- and low-market level customers. They have more pressing needs and, as we shall see, they are legion.

4 TRENDS IN MACHINE TOOL DEMAND

4.1 Global overview

7.2 billion strong today, the world’s population is forecasted to reach 8.1 billion in just over a decade and 9.6 billion by 2050 with nearly all of the growth occurring in developing countries.[1][2] Only 1.25 billion people around the world live in developed countries, yet these are the markets that current machine tool research and design efforts almost exclusively target. The amount of potential buyers for high-end machine tools in Africa hardy justifies the cost overhead of setting up a retail outlet!

4.2 Regional highlights

The coming sea-change in economic influence is as predictable as it is unavoidable. Markets which were once afterthoughts, customers both overlooked and ignored, are tomorrow’s most sought-after commodity.

The economies which dominated the latter half of the 20th century will be marginalized by the middle of the 21st as Figure 1 from the OECD aptly illustrates.

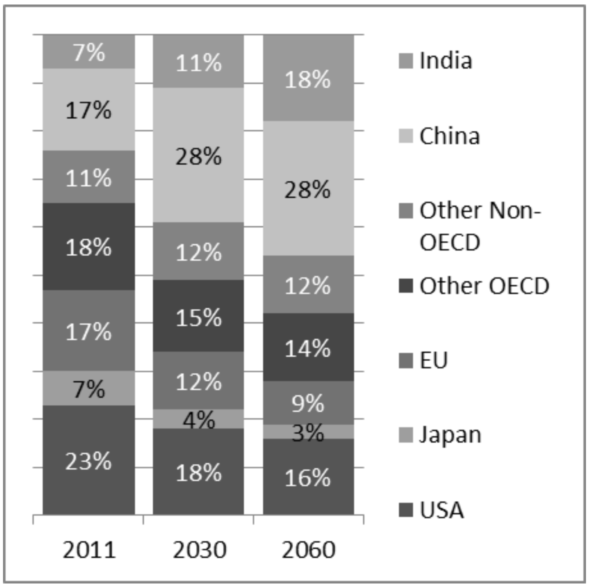


Figure 1: Forecasted % of global GDP.[3]

While this impending economic transition is well-understood, far less time has been spent considering the product demand implications of such a shift. As an example, in 2010 China overtook Japan to become the world’s second largest economy but three years later many industries are still grappling with how to design, develop, and market products from the ground up for the Chinese consumer.[4]

The machine tool industry is no exception. Despite clear data regarding on-going demographic and economic shifts, key manufacturers have yet to begin tailoring their products to these new markets.

While manufacturing needs are broadly consistent, it is not so simple as localizing documentation and certifying quality under new legal frameworks. Failure is certain if manufacturers don’t respect the characteristics of these new markets. Time must be taken to understand their manifold differences in everything from history and culture, to behavior patterns, communication methods, and work-life balance.

5 THE INTERNET AS GAME-CHANGER

5.1 Who is online?

Three billion people will be online by 2016. It is expected that nearly 4/5ths of all broadband devices will be mobile. In 2005 within the G-20 countries 68% of online users were from developed nations. By 2015 that ratio is expected to flip: 67% of the online community will be in developing countries.[5]

What’s more, these developing country user bases are comfortable with a far higher average level of Internet technology than their developed country peers. As economic latecomers, they were non-participants during the early decades. To them there is no ‘Web 2.0’ because they didn’t experience Web 1.0, there is simply the Internet. This makes them comparatively flexible and quicker to embrace new technologies, when they can be afforded.

5.2 The new players

Generation Y is now climbing the corporate ladder. While they have yet to ascend high enough to directly influence purchasing decisions, they dominate the factory operator ranks.

Whereas their predecessors painstakingly adapted to each new increment in computerized manufacturing, Generation Y has grown up with email, mobile phones, and instant messaging. Touch screens are a standard feature, not a frivolous optional accessory. Manual tool controls are unthinkably inefficient.

The manufacturing environment these young, talented individuals are entering is the twilight era of computer integrated manufacturing. Computer-aided drafting, engineering, production, quality, and management – all breakthroughs at one time – are now industry standards. Rather than ask a candidate if they are familiar with CAD, one inquires as to which platforms they've used and with which programming languages they are fluent.

The stage has been set for the next great leap forward.

5.3 Industry 4.0 & Impact on manufacturing

After successive decades of diminishing manufacturing R&D returns on efficiency, productivity, and flexibility a new era of unprecedented potential is almost upon us.

The simultaneous arrival of a technologically adept global workforce, deep penetration of Internet access around the world, and the rise of emerging economies is creating a synergy that will transform the entire manufacturing industry – the era of 'Internet Driven Manufacturing' (IDM) is on the horizon.

Via IDM a design engineer in Bangalore can upload her CAD schematics to a cloud marketplace and production solicit bids from a family-owned shop on the outskirts of Jakarta. Via IDM a factory foreman from Kenya can use his mobile phone to monitor production and issues orders while attending a lecture during a symposium in Johannesburg. Via IDM a service engineer in Berlin can fly overnight to São Paulo and pay a service call to his key customer before they are even aware something is wrong because the machines have automatically notified their manufacturer.

Succeeding in Industry 4.0 will require talented personnel, comprehensive IT infrastructure, economic strength, and enlightened manufacturers.

6 HOW CHINESE MACHINE TOOL MANUFACTURERS ARE ADAPTING

As the world's shop floor, and with the largest Internet community on Earth, China stands ready to make the most of Industry 4.0.

6.1 Strategic innovation

Long noted for their ability to imitate and adapt the designs of others, the Chinese manufacturers are beginning to blaze their own path. With nearly 50% of all machine tools in the world sold domestically, Chinese manufacturers are virtually right next door to their most important customers. With strong central government support, the industry has moved beyond asking 'what' and is now entering a phase of 'strategic hows':

- How can we help our customers reach their own goals?
- How can we minimize capital risk and thereby lower the bar to market entry?
- How can we generate new revenue from products already in the field?
- How can we capitalize on the technical savvy of our customers?
- How do we differentiate ourselves in an era of technological homogenization?

The corporations which can answer these questions are tomorrow's industry titans.

6.2 'Co-Operations'

Those that do attempt to answer the questions above are beginning to understand that within the manufacturing industry no one entity is in position to provide all the know-how, services, and equipment that the 21st century customer needs. Furthermore, there isn't time to develop the missing capabilities. The market cannot wait.

The solution as we are now seeing today is the rise of 'Co-Operations' within the manufacturing industry. Companies are moving beyond the traditional vendor-client relationship to create harmonious partnerships. Rather than providing the customer a list of 'manufacturer approved' third-party accessories providers, companies are now approaching the customer as a team with a portfolio of complimentary products and services.

6.3 Embracing global cooperation

To their credit, the Chinese manufacturers are not just reaching across corporate lines, they are crossing borders as well. The machine tool industry has technological and industrial hubs in North America, Europe, and East Asia. Chinese manufacturers are actively seeking out international partners with complimentary capabilities to create highly effective, well-rounded alliances. What was once a corporate climate of defiant independence is giving way to the realization that ably standing on equal footing with other industrial champions has yet more merit.

7 NEXT GENERATION MACHINING

7.1 Development trends

Machine tool manufacturers are turning away from chasing ever smaller fractional gains in cutting speed and accuracy, and are instead attacking other aspects of the complicated modern machining process. The following areas are where future growth potential is found.

7.2 'SMART' products

First and foremost, '**S**MART**'** machine tools are *simple*. That is not to say they lack features or capability. On the contrary, the next generation of machine tools are more feature-rich and flexible than any before. Rather, careful attention is paid to make the user experience as logical, comfortable, and effortless as possible. In this way new operators can quickly make strong contributions to production.

Secondly, 'S**M**ART' machine tools are *maintenance-friendly*. In this industry downtime as an event is unavoidable, but its nature and duration can be controlled through intelligent design.

Thirdly, ‘SM**A**RT’ machine tools are *affordable*. Global economic growth for at least the next three decades will be concentrated in markets for whom the machine tool high-end segment is wholly out of reach.

Fourth, ‘SMA**R**T**’** machine tools are *reliable*. While the technological gap between low- and high-end machine tools has narrowed considerably, reliability differences remain. Next generation machine tools will allow mid- and low-level customers to operate round-the-clock worry-free.

Lastly, **‘**SMAR**T’** machine tools are *timely* to market and profit. In other words they must be quick to build, customize, deliver, and succeed. This will be accomplished via the widespread adoption of modular design principles which have already been put to great use in other industries and by actively engaging the customer at all steps of the business process.

7.3 ‘SMART’ enterprises

Creating these new **smart** products will be **smart** enterprises. Multidisciplinary, multicultural, and egalitarian, these corporations will present their customers with efficient, flexible, customized interactions at all stages of the business process.

While long-term strategy will still be set by a core group of visionaries, frontline employees will be empowered with the authority necessary to resolve any and all customer issues.

The corporation will be able to marshal expansive resources to meet market needs while still presenting a personal link to individual customers.

7.4 New business model

An industry once characterized by a ‘sell and forget’ mentality is speeding towards an integrated solutions provider business model with sustainable manufacturing at its core.

Well-built machine tools have a life-expectancy measured in decades, but the needs of individual customers develop on the order of years. Establishing comprehensive upgrade, refurbishment, and buyback operations allows for still-useful equipment to find its way into the hands of grateful new owners while freeing the original customer to invest in greater hardware.

The 2008 financial crisis and ensuing collapse of lender credit had a devastating impact on the manufacturing industry. Operating on already tight cash flows, when credit lines dried up SMEs found themselves caught in a vicious cycle: unable to purchase new tooling they could not receive new orders, unable to receive new orders they could not generate the cash necessary to purchase new tooling. Credit liquidity has been slow to return. Forward-thinking machine tool manufacturers are filling this void by developing their own internal financing mechanisms. Customers are responding very positively as they realize their interests of their creditor and business partner are finally aligned, since they are the same entity.

8 CONCLUSION

The machine tool industry’s decades-long pursuit of speed and accuracy is fast coming to an end. The rise of the wired populace, optimization of global communications infrastructure, and growing importance of developing economies heralds a new era of machining and a new definition of ‘best’ product. Ergonomics, reliability, digital integration, and robust product portfolios are the keys to the next generation. China, due to its role as the world’s workshop, its tremendous online population, and its economic strength is uniquely positioned to lead the coming revolution of sustainable, smart manufacturing.

9 REFERENCES

[1] United Nations, Department of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision, Press Release (13 June 2013): "World Population to reach 9.6 billion by 2050 with most growth in developing regions, especially Africa".

[2] United Nations, Department of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision, Highlights and Advance Tables. ESA/P/WP.228

[3] Johansson, Å., et al. (2012), "Looking to 2060: Long-Term Global Growth Prospects: A Going for Growth Report", OECD Economic Policy Papers, No. 3, OECD Publishing.

[4] Hamlin, Kevin, and Yanping Li. "China Overtakes Japan as World's Second-Biggest Economy - Bloomberg." Bloomberg - Business, Financial & Economic News, Stock Quotes. N.p., 16 Aug. 2010. Web. 3 Sept. 2013. <http://www.bloomberg.com/news/2010-08-16/china-economy-passes-japan-s-in-second-quarter-capping-three-decade-rise.html>.

[5] Dean, David, et al. "The Internet Economy in the G-20." bcg.perspectives. Boston Consulting Group, 19 Mar. 2012. Web. 3 Sept. 2013. <https://www.bcgperspectives.com/content/articles/media_entertainment_strategic_planning_4_2_trillion_opportunity_internet_economy_g20/>.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

A Brazilian perspective on remanufacturing

Rozenfeld, H.[1]; Barquet, A. P.[1],

[1] Department Industrial Engineering, University of Sao Paulo, Sao Carlos, SP, Brazil

Abstract

The goal of this paper is to give further information concerning the Keynote “A Brazilian perspective on sustainable manufacturing and remanufacturing” held on the 11th CIRP Conference on Sustainable Manufacturing. Therefore, this paper contains the description of the current Brazilian situation in terms of poverty, social inequalities and violence and in contrast the country’s abundance of natural resources. Thus, it is reported how this current situation is associated with sustainable development, mainly in the Brazilian industrial sector. Finally, an example of a sustainable approach to be adopted by companies within this context is given, namely remanufacturing.

Keywords:

Brazil: Sustainability; Brazil Industry; Remanufacturing.

1 INTRODUCTION

Brazil is an emerging country which influence in the international trade and politics has been steadily growing since the last decades, mainly because the country offers great perspectives for sustainable development. However, the country’s main drawbacks are related to weak public healthcare systems and more generally a lack of infrastructure hampers its development.

The goal of this paper is to describe the Keynote “A Brazilian perspective on sustainable manufacturing and remanufacturing” held on the 11th CIRP Conference on Sustainable Manufacturing.

An overview of the current strengths and weaknesses of Brazil is given in general terms, and associated with the opportunities of the country to use sustainable development as a main driver for the growth of its industry.

2 BRAZIL: A COUNTRY OF CONTRADICTIONS

2.1 Positive side: abundance of natural resources

Brazil has a great amount of natural resources, which highlights the importance and the responsibility of the country in the current global scenario of limited resources and growing consciousness towards the need for sustainability.

For instance, almost 50% of the national energy supply comes from renewable sources. Also, the country presents the world's largest stock of the carbon stored in forest biomass, as it has the largest area of rainforest and the second largest forestry. The forest area covers 60% of the country’s territory. In addition, approximately 12% of the planet's available surface water is located in Brazil [1].

The country contains a large territory covered by natural parks, extractive reserves and indigenous lands. There are 68 units of natural parks with an extension of 38.325.615 ha (hectare) [2], 22 units of extractive reserves covering 3.407.915 ha [3] and 608 units of indigenous lands in 109.741.229 ha [4]. The indigenous lands territory represents 13% of all the Brazilian territory.

The sum of these three types of territories covers 151.474.759 ha, which is four times the extension of the Germany territory, which is 35.702.100 ha [5].

2.2 Negative side: poverty, social inequalities and violence

One of the Brazil most spread characteristics is its high poverty rate. 23.6% of the population lives in families with an income below the poverty line. Since Brazil has big proportions and population, this 23.6% represents between 16 and 25 million people [6].

Yet, Brazil is among the 10 countries with the highest rates of social disparity. The main reasons leading to this disproportion are [7]:

- The lack of access to education;
- Unfair fiscal policy;
- Low wages and lack of basic services, such as health, transport and public sanitation.

The large numbers associated to violence are also refraining further social integrity, mainly when it comes to the use of firearms. 70% of homicides in the country are committed with firearms. As an illustration of the last years situation, in 2010, more than 106 persons were killed by means of firearms every day [8].

These numbers are even more alarming when it comes to homicides per young people. The rate of 54.8 homicides per 100,000 young people is 137 times higher than the rates of Germany [8].

Despite the fact that Brazil is a country without territorial disputes, emancipatory movements, religious confrontations, racial or ethnic, border conflicts or terrorist acts, it is difficult to deny that the country holds a civil war. Between 2008 and 2011, a total of 206,005 died victims of homicides in Brazil, resulting in a higher casualties number than the deaths occurred during the 12 major armed conflicts that took place in world between 2004 and 2007 [8].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

2.3 Growth of consciousness of Brazilian Society

Some recent movements and actions in Brazil have been retaining the attention of the global news stream. The most significative one occurred between April and June of 2013, when thousands of Brazilian went in the streets to demonstrate their dissatisfaction with the alarming current situation in Brazil in terms of public infrastructure management, as well as the lack of improvement measures from the government.

The trigger fuse to start the manifestation was the increase of 0.20 cents in the bus fare on public transport in the states of São Paulo and Rio de Janeiro. More than 100,000 people went on the streets and most of them were young people on age between 17 and 25 [9].

An important event is about to happen in Brazil, the World Cup on 2014. Regarding this event, example of sustainability actions can be outlined. The Environment Minister Izabella Teixeira highlighted five actions of the sustainability agenda regarding World Cup in Brazil [10]:

- Management of solid waste in the host cities;
- Expansion of the structure to receive tourists in the Parks Cup (as Foz do Iguaçu and Fernando de Noronha);
- Decrease of the emission of greenhouse gases;
- Encouraging the production of organic food;
- Grant of a Seal of Sustainability to companies and organizations.

The manifestations point out the necessity for the Brazilian government to pay attention to the social dimension, since society seems to be expecting concrete actions from the politicians. On the other side, the actions presented by the Environment Minister for World Cup shows an increasing public consciousness regarding the sustainability aspects. Another relevant point to be treated is the status of sustainability on the Brazilian industry.

3 SUSTAINABILITY ON BRAZILIAN INDUSTRY

Plenty of challenges and opportunities are identified when it comes to sustainability on the Brazilian industry.

3.1 Challenges of sustainable development on Brazilian industry

Some factors hinder the development of sustainability in the Brazilian industrial sector. These factors are described below: [1].

One important fact is the distortions within the Brazilian tax system. The unjustified diversity of taxes and frequent changes in the format of Brazilian taxation increases complexity to make changes and improvements to the current system.

High costs to access credit and interest rates can also be considered a problem since it hampers the access to long term credit for enterprises, mainly for micro and small companies.

Another factor is associated with the lack of policy instruments favoring R&D and innovation for sustainability and the lack of coordination among public and private institutions to work together, aligned with national innovation and sustainability strategies.

Instability, inadequate management and regulatory frameworks in the environmental area are also factors that hinder the development of sustainability in the Brazilian industrial sector. The focus of environmental public management is limited to licensing and permitting activities, instead of considering incentive actions to stimulate Brazilian companies on the adoption of environmental actions.

Insufficient and poor quality of infrastructure services are also challenges on sustainability adoption. The greatest lack of services is on the areas of transportation and sanitation.

Last but not least, education sector appears as a dismissed sector, especially within the public primary and secondary education system. This causes a lack of basic education and environmental awareness of the population regarding the importance of a sustainable development and also an insufficient number of skilled workers to aliment the growing human resources needs from the Brazilian economy

3.2 Opportunities of sustainable development on Brazilian industry

In spite of the challenges described in the session 3.1, Brazilian industry presents numerous opportunities for industrial sustainable development [1].

An opportunity is the investment on wind and solar energy. Currently, they are underutilized in Brazil. Regarding biodiversity, Brazil harbors covers about 15% of all species on the planet, however only a small portion is known. Exploiting the potential of biotechnology is presented as advancement opportunity for Brazilian industry, mainly for the pharmaceutics sector.

An important action is the creation of incentives such as "Climate Fund“, which aims to finance projects that target mitigation and adaptation of climate change and its effects.

In addition, investment in research, technological development and innovation are a source of opportunities to increase efficiency, reduce costs and develop new business.

Opportunities can also be associated to the solid waste management, which aims to stimulate the reuse of products and materials as inputs in the production system. Brazil is an international benchmark for waste recycling in activities that also contributes to social inclusion.

It is also relevant to considerer that the changes required for a sustainable development pattern depends on both public and private investment, particularly in cleaner production technologies and innovative methods in business management.

Concerning innovative ways to reach sustainable actions on the business, remanufacturing is an approach that can support companies on developing actions on the three pillars of sustainability [11].

4 REMANUFACTURING: EXAMPLE OF SUSTAINABLE APPROACH TO BE ADOPTED BY BRAZILIAN INDUSTRY

4.1 Definition of remanufacturing

Some approaches are being adopted by companies for defining recovering strategies for products that reaches their end of life (EOL). Beside waste reduction, remanufacturing is the most promising strategy for enabling several product life cycles.

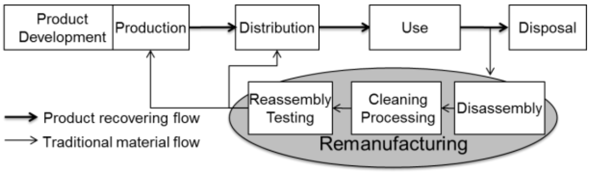


Figure 1: Traditional and reverse material flow.

The EOL product, also named core, returns to the production process and pass thought steps like disassembly, cleaning, repair, inspection and assembly. The remanufactured product is characterized by having the same quality and warranty as a new one. In addition, remanufacturing process preserves part of the value added to the product during its manufacturing, allowing companies to increase resource efficiency and productivity [12].

Motivations to implement remanufacturing can be highlighted. By performing remanufacturing, companies can increase market share gain as well as contribute toward more sustainable production and consumption [13-14].

In Brazil, only few Brazilian companies are committed with the final destination of the used products they manufactured. However, this situation might change in the near future because of to the enacted National Policy on Solid Waste in 2010. The objective of this law is to stimulate Extended Producer Responsibility (EPR) [15].

4.2 Remanufacturing oriented project

Aiming to stimulate the adoption of remanufacturing by companies, the project named "Networking small and medium sized enterprises for competitive remanufacturing" is being carried out by Technische Universität Berlin (Prof. Dr.-Ing. Günther Seliger) and Universidade de Sao Paulo (Prof. Dr.-Ing. Henrique Rozenfeld). This project is part of the BRAGECRIM Program - Brazilian and Germany Collaborative Research Initiative in Manufacturing.

The goal of the project is to create new potentials for competitive advantages by providing guidelines to key actors of remanufacturing networks. To reach that goal, an online guideline is being created in order to support companies on defining remanufacturing oriented business models.

4.3 Guideline for remanufacturing business models

The guideline is composed of business models dimensions ad templates associated with each dimension. The dimensions of the guideline are adapted from Canvas business models and its nine elements: customer segments, value propositions, channels, customer relationships, revenue streams, key resources, key activities, key partnerships and cost structure [16].

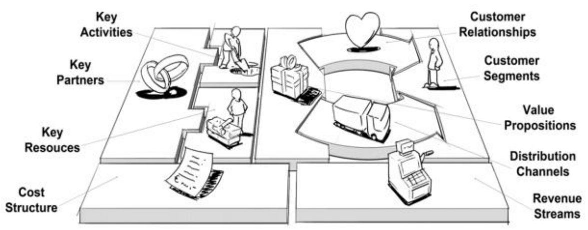


Figure 2: Canvas Business Model [16]

For each dimension, the user has inputs, tools, free outputs and attributes available to support him on the definition of the important characteristics of a specific business model dimension.

Each dimension has a template associated, which the user can download on the website and fulfill it according to options and choices he makes about his own remanufacturing business. The user can fulfill the templates following the information available on the dimensions.

Therefore, the guideline enables the design of the current or future business model based on selection of different remanufacturing attributes. In addition, new business opportunities for new entrants and improvements on current remanufacturing business can emerge.

5 FINAL CONSIDERATIONS

This paper described the Keynote "A Brazilian perspective on sustainable manufacturing and remanufacturing" held on the 10th CIRP Conference on Sustainable Manufacturing.

By introducing Remanufacturing as an approach to reach sustainability on industry, challenges and opportunities discussed on session 3.1 and 3.2 are implied. First of them concerns solid waste management. By making remanufacturing, enterprises need to create mechanisms to take back the product on its EOL, avoiding the increase of industrial waste and enabling a more efficient use of resources. The second point is related to technology and innovation. By adopting remanufacturing, companies may require the development of new technologies, e.g. for cleaning the product, and also the adaption or creation of new business models, which can lead to innovative business. The third point covers the social inclusion by increasing number of jobs. The development of the remanufacturing industry will demand more workforce, mainly because remanufacturing is labor oriented, with few possibilities for further automation processes.

6 REFERENCES

[1]CNI (Confederação Nacional da Indústria). A Indústria Brasileira no Caminho da Sustentabilidade. Brasília: CNI, 2012.

[2]www.icmbio.gov.br/. Access on September, 2013.

[3]http://www.ibama.gov.br/resex/resex.htm. Access on September, 2013.

[4]http://www.funai.gov.br/index.html. Access on September, 2013.

[5]http://www.eurice.info/typo3sites/fileadmin/x_incs/Germany.pdf. Access on September, 2013.

[6]http://g1.globo.com/politica/noticia/2011/05/brasil-tem-1627-milhoes-de-pessoas-em-situacao-de-extrema-pobreza.html. Access on September, 2013.

[7]http://desigualdade-social.info/mos/view/Desigualdade_Social_no_Brasil/. Access on September, 2013.

[8]http://mapadaviolencia.org.br/pdf2013/mapa2013_homicidios_juventude.pdf. Access on September, 2013.

[9]fcnoticias.com.br. Access on September, 2013.

[10]Ascom - Ministério do Esporte. http://www.copa2014.gov.br/pt-br/noticia/ministra-do-meio-ambiente-comenta-acoes-de-sustentabilidade-na-copa-do-mundo-da-fifa-2014. Access on September, 2013.

[11] Guidat, T., Barquet, A.P., Hamamoto, T., Zorzal dos Santos, J.A., Oliveira Gomez, J., Rozenfeld, H., Seliger, G. 2013. An analysis of industrial networks for remanufacturing in Brazil. 22nd International Conference on Production Research. Foz do Iguaçu, Brazil.

[12] Giuntini, R., Gaudette, K. 2003. Remanufacturing: the next great opportunity for boosting US productivity, Bus Horiz, 46/6: 41-48.

[13] Barquet, A.P., Rozenfeld, H., Forcellini, F.A., 2013, An integrated approach to remanufacturing: model of a remanufacturing system, Journal of Remanufacturing, 3: 1–11.

[14] Amezquita, T., Hammond, R., Salazar, M., Bras, B. 1995. Characterizing the remanufacturability of engineering systems. Proceedings of ASME Advances in Design Automation Conference. Boston, Massachusetts.

[15] National Solid Waste Policy (Politica Nacional de Residuos Solidos – Lei No, National Solid Waste Policy (Politica Nacional de Residuos Solidos – Lei No. 12.305/2010). Presidência da Republica. Brasil. (in Portuguese).

[16] Osterwalder, A.; Pigneur, Y. 2009. Business Model Generation. Amsterdam: Self Published.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

Innovation in sustainable manufacturing education

I.S. Jawahir, F. Badurdeen and K.E. Rouch
Institute for Sustainable Manufacturing (ISM)
University of Kentucky
Lexington, KY, USA

Abstract
Sustainable value creation entails generating value for all stakeholders from economic, environmental and social perspectives. In a manufacturing context, creating sustainable value requires product, process and systems level innovations to enable near-perpetual closed-loop material flow across multiple life-cycles; it also requires understanding the complex interactions of the socio-technical systems with the natural environment for emergent synthesis so sustainable value creation can occur harmoniously and continuously. However, current educational curricula with traditional disciplines is fragmented and do not represent the multi-disciplinarity or the integration needs; it is now necessary to work at the interface of the various disciplines to address the complex issues that are brought about through sustainability. Thus, to create sustainable value through sustainable manufacturing will require transformational and innovative reforms in education with an overall paradigm shift to provide the future generation of engineers, scientists and managers the necessary technical knowledge, skills and capabilities. This paper presents recent trends in developing such innovative educational programs in sustainable manufacturing. Also, the technological challenges posed by the need for implementing viable innovative sustainable manufacturing educational programs inevitably require fundamental studies on total life-cycle products, closed-loop manufacturing processes and integrated production systems extending beyond to the entire supply chain operations. This paper is aimed at tackling these significant challenges by essentially developing sustainable value propositions for all forms of educational programs (formal degrees and certificate level programs, professional/continuing education programs, short courses and web-based interactive learning programs, etc.) to incorporate the new knowledge needed to promote value-added sustainable manufacturing at product, process and system levels.

Keywords:
Sustainable manufacturing, innovation, education, curriculum development

1 INTRODUCTION

With continuously increasing awareness and the need for sustainable products and processes, a strong emphasis needs to be placed on developing education and training programs including relevant curricula for engineers and scientists of the future to provide the basic theories and applications of sustainability science involving product life-cycle engineering and sustainability principles for societal, economic and environmental benefits. Over the last few decades, traditional manufacturing/production engineering educational programs have long depended on curricula based on concurrent engineering methodologies covering product and process designs, functional design development, concept selection for product design, materials and process selection, process planning including assembly analysis, etc., all aimed at optimally selected designs and manufacturing practices for economic manufacturing. These programs however suffer from the lack of consideration of sustainability principles.

While significant progress is being made in new curriculum development and/or updating current curriculum to incorporate sustainability principles and practices in manufacturing, more needs to be done, particularly in the broader sustainability perspective, to cover the entire production system. This would require full understanding of the total life-cycle effects involving innovative methods for products, processes and systems involved in manufacturing. Attempts must also be made to maintain the holistic objective given by the overall sustainability requirements in industrial production for which educational programs must be significantly revised. It has been shown that efforts to make manufacturing more sustainable must also consider sustainability issues at all relevant levels: product, process, and system [1]. At the product level, there is a need to move beyond the traditional 3R concept promoting green technologies (reduce, reuse, recycle) to a more recent 6R concept forming the basis for sustainable manufacturing (reduce, reuse, recycle, recover, redesign, remanufacture), since this allows for shifting from an open-loop, single life-cycle paradigm to a more meaningful, closed-loop, multiple life-cycle paradigm [2]. At the process level, there is a need to model and achieve optimized technological improvements and develop process planning to reduce energy and resource consumptions, toxic wastes, occupational hazards, etc. without compromising the product quality or the manufacturing productivity [3]. At the system level, there is a need to consider all aspects of the entire supply chain, by taking into account all the major life-cycle stages – pre-manufacturing, manufacturing, use and post-use – over multiple life-cycles [4].

This paper presents an overview of recent trends, and new challenges involved in developing educational programs

ISBN 978-3-7983-2609-5

and/or updating curriculum for producing next generation engineers and scientist with adequate and relevant knowledge for achieving overall sustainability at the product, process and system levels in industrial production.

1.1 The role of education and training in sustainability applications for manufacturing

Sustainability as the driver for innovation*:* Numerous studies and in-depth analysis of sustainability concepts and applications have shown that sustainability is a driver for innovation. The most notable among these studies include an early work published in the Harvard Business Review [5] which presents a five-stage approach with central challenges and competencies required, and the innovation opportunities discussed for each stage:

Stage 1: Viewing compliance as opportunity;
Stage 2: Making value chains sustainable;
Stage 3: Designing sustainable products and services;
Stage 4: Developing new business models; and
Stage 5: Creating next practice platforms.

A more recent MIT study [6] shows that many companies are generating profits from sustainability. They recommend five practices to accomplish this:

- Need to change the business model
- Leading from the top to integrate the effects
- Measuring and tracking sustainability goals and performance
- Understanding the customer expectations for sustainability in terms of value and cost
- Collaborating with individuals, customers, businesses and groups beyond the boundaries of the organization

Innovation promotes accelerated growth in manufacturing*:* It is well-known that innovation in industrial production with advancement of product and process technologies leads to technological advances with competitive advantage, and this promotes accelerated growth in manufacturing. Sustainable products and processes are known to be innovative, and they contribute to societal and environmental benefits, too.

Manufacturing is the engine for wealth generation and societal well-being*:* National economy of any country heavily depends on the manufacturing capacity and the diversity of products and processes developed for its population, and for marketing to other nations. Developed and developing nations have shown the pivotal role of manufacturing in job creation, societal well-being and national economic advancement.

Societal well-being and economic growth heavily depend on the level and quality of education and training*:* Education and training of workforce are essential elements for economic and social growth of any nation. Such education and training programs in sustainability are also a strategic requirement for nations, communities and individuals. Thus, innovation is vital for promoting sustainable manufacturing that is an engine for more sustainable growth and education and training play a strategic role in enabling this future.

1.2 Sustainable manufacturing: Definition

Sustainable manufacturing deals with three integral elements: products, processes and systems. To achieve sustainable production, each of these three integral elements is expected to demonstrate:

(a) reduced negative environmental impact,
(b) offer improved energy and resource efficiency,
(c) generate minimum quantity of wastes,
(d) provide operational safety, and
(e) offer improved personal health

while maintaining and/or improving the product and process quality.

There are numerous definitions and descriptions for sustainable manufacturing. However, almost all such definitions fall short of showing the connectivity among the above integral elements. Sustainable manufacturing offers a new way of producing functionally superior products using sustainable technologies and manufacturing methods through the coordination of capabilities across the supply chain. Thus, integrated sustainable manufacturing focusing on product, process and system levels must ultimately enable sustainable value creation for all stakeholders. This entails following a co-creative model to generating value through sustainable manufacturing where value generation is approached broadly from a systems thinking perspective by taking account of the dependencies between the producer, the consumer as well as the product/service and the wider social and natural environment, as opposed to manufacturers simply providing value independent of the other stakeholder needs (providing value model) or value being assessed based only on the interactions between the product/service and the environment (Adaptive Model) (Figure 1) [7].

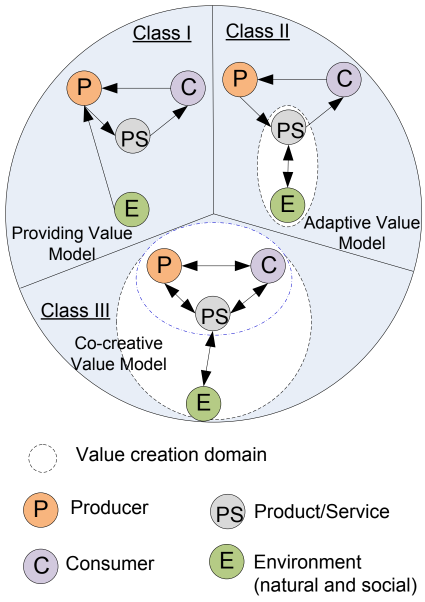


Figure 1: Sustainable value co-creation models (Based on [7]).

2 REVIEW OF RELEVANT LITERATURE ON EDUCATIONAL NEEDS FOR SUSTAINABLE MANUFACTURING

There is a large domain of literature on engineering education applied to manufacturing in general. More recently, an increasing trend is noted in published material covering specific aspects of environmental and sustainable engineering programs. This is due continuing awareness of sustainability issues by the society at large and the new and attractive research funding opportunities that have come to exist. As the industrial sector continues to embrace sustainable manufacturing technologies, universities and institutes of higher learning are increasing their curriculum development activities to match the industry needs and to satisfy the stakeholders at large.

An early work presents an educational program for sustainable futures largely based on environmental concerns [8]. Concepts of global competitive sustainable manufacturing are shown for creating the knowledge base of competitiveness and sustainability from education, research and innovation [9]. To accomplish sustainable industrial systems enabling the delivery of high value, the emerging role of systems thinking in education, research and industrial practices was emphasized with specific recommendations [10]. Educational challenges involved in preparing future engineers in the U.S. with sustainable engineering fundamentals were summarized from the efforts of Center for Sustainable Engineering (CSE) through documented activities of national level workshops, roadmap assessment and the development of an electronic library [11]. This follows an earlier extensive study of sustainable engineering education and research in U.S. universities [12-14] and an international comparative study of sustainability education [15]. Also, a more specific comparative study of undergraduate educational programs in selected U.S. universities has been reported [16]. New challenges involved in developing educational programs to introduce design for sustainability principles and practices were also presented [17]. More recently, an extensive review of sustainable manufacturing research emphasizes the need for developing educational programs for future engineers with a broad-based understanding of product and process design, material processing and manufacturing by highlighting their influence across the entire life-cycle [18].

3 SUSTAINABLE VALUE FROM INNOVATIVE PRODUCTS, PROCESSES AND SYSTEMS

3.1 General Background

Developing innovative products, processes and systems is a significant aspect of sustainable manufacturing, and it involves a holistic approach to manufacturing different from the traditional manufacturing practices where the quality and performance characteristics are measured and quantified independently, often with no consideration of the effects of other integral elements. While integrated product – process design methodologies have largely been based on concurrent engineering applications, involving team of "experts" from multi-disciplinary fields, territorial boundaries and responsibilities with varying reporting structures of team members, unless centrally managed, often have prevented these experts from going across the boundaries of their units and/or organization to participate in developing innovative products, processes and systems. The emerging holistic and integrated approach requires all stakeholders to work together on common objectives with total commitment. To enable innovation in sustainable manufacturing, innovation must be embraced at the product, process and systems levels with close interactions among each other as shown in Figure 2.

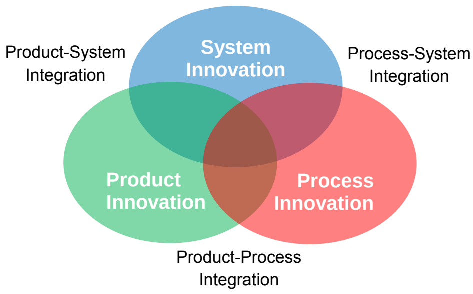


Figure 2: Innovation in sustainable manufacturing at integrated product, process and system levels.

Fully integrated sustainable manufacturing will emerge as an effective platform for developing sustainable products from sustainable processes and with related system integration. Examples of constituting innovative aspects in sustainable manufacturing are shown in Figure 3 for each component of innovation. The innovation must enable developing an integrated sustainable value system for sustainable manufacturing with numerous value-contributing factors: value propositions such as technological value, socio-economic value, socio-political value, and socio-environmental value, etc., can be derived from this integrated system.

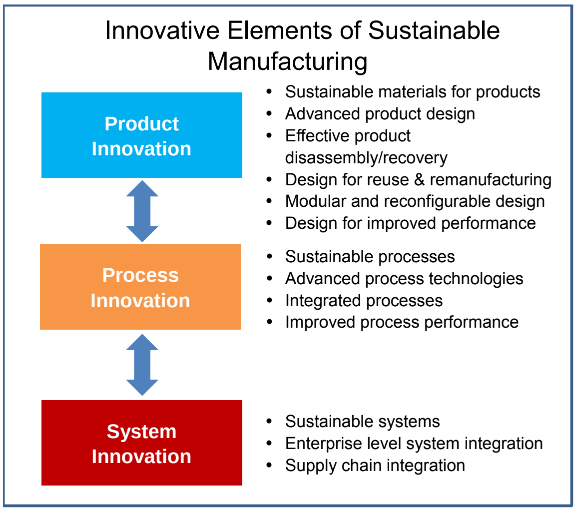


Figure 3: Examples of innovative aspects in sustainable manufacturing at product, process and system levels.

3.2 Sustainability Issues at the Product and Process Levels

Since there are multiple streams of energy, material and waste/emission involved at different stages over a product's life, the necessity of considering the total life-cycle in order to evaluate a product's sustainability score for comparison between different designs, or between different production strategies, is well recognized. Graedel [19] presented an extensive study of streamlined life-cycle analysis (SLCA) methods in a pioneering textbook covering various methodologies, including matrix approaches using target plots, and considering five major product life-cycle stages: pre-manufacture; manufacture; product delivery; use; and recycling. Subsequently, the product delivery, including transportation, was considered as only one among several delivery activities involved in all stages of the product's life-cycle, hence the simplified total life-cycle of a product was assumed to consist of four key stages – pre-manufacturing, manufacturing, use and post-use [2]. To achieve multiple product life-cycles with the goal of near-perpetual product/material life, design and manufacturing practices for next-generation products must consider these product life-cycle stages using a more innovative 6R approach, and then build a comprehensive systems model to cover products, processes and systems to enable value creation through innovation at all levels.

Product sustainability*:* Several researchers have considered the environmental performance and the associated economic and societal effects of products, largely intuitively, and offering limited quantitative descriptions. Thus, these analyses mostly remain non-analytical and less scientific in terms of the need for quantitative modeling of product sustainability. Moreover, the partial treatment and acceptance of the apparent effects of several sustainability-contributing measures in relatively simplistic environmental, economic and societal impact categories has virtually masked the influence of other contributing factors such as product's functionality, manufacturability, reusability with multiple life-cycles, etc. Consideration of a total and comprehensive evaluation of product sustainability can lead to reduced consumer costs over the entire life-cycle of the product, while the initial product cost could be slightly higher in some cases. This benefit is compounded when a multiple life-cycle approach is adopted on the basis of continuous material flow. The overall economic benefits and the technological advances involving greater functionality and sustained quality enhancement are far too great to outscore with the current practice. The technological and societal impacts are also significant.

Recent research on product sustainability evaluation shows a consistent trend towards the long-range development of a product sustainability rating system for all manufactured products. This rating would be expected to represent the "level of sustainability" built in a product by taking into account all major contributing sustainability elements and their sub-elements. Early work shows the following six product sustainability elements [2]:

(a) Environmental Impact
(b) Societal Impact (Safety, Health, Ethics, etc.)
(c) Functionality
(d) Resource Utilization and Economy
(e) Manufacturability
(f) Product's Recyclability/Remanufacturability

These interacting elements and sub-elements need to be fully studied for their effects on product sustainability. Other influencing elements and sub-elements will be identified as appropriate. This systematic study should provide a solid foundation for involving relevant "priority roles" and "trade-offs", when this project is extended to the next level. Our preliminary work in this area also considered ratings at all three levels (sub-element, element and overall).

Process sustainability*:* The primary objective of identifying and defining the various contributing elements and sub-elements of manufacturing process sustainability is to establish a unified, standard scientific methodology to evaluate the degree of sustainability of a given manufacturing process. This evaluation can be performed irrespective of product life-cycle issues, recycling, remanufacturability, etc., of the manufactured product. Manufacturing processes are numerous, and depending on the product being manufactured, method of manufacture, and their key characteristics, these processes differ very widely. This makes the identification of the factors/elements involved in process sustainability and the demarcation of their boundaries complex. For example, if the production process of a simple component is considered, it goes through a few clearly defined production stages; component design, tool/work material selection, metal removal/forming, finishing, packaging, transporting, storage, dispatching, etc.

It is extremely difficult to consider all of these stages in evaluating manufacturing process sustainability though they either directly or indirectly can contribute to the manufacturing process sustainability. Also, the processing cost largely depends on the method used to produce the part/component and the work material selected. In a never-ending effort to minimize the manufacturing costs, the industrial organizations are struggling to maintain the product quality, operator's and machine safety, and power consumption. If the processing includes the use of coolants, lubricants, emission of toxic materials or harmful chemicals, this poses environmental, safety and personnel health problems. In general, among the various factors, the following six factors can be regarded as significant to make a manufacturing process sustainable:

(a) Energy consumption
(b) Manufacturing cost
(c) Environmental impact
(d) Operational safety
(e) Personnel health
(f) Waste reduction

The motivation for recent sustainability studies of manufacturing processes comes from recent efforts in developing a manufacturing process sustainability index. The idea in developing this concept is to isolate the manufacturing process from the global picture of sustainability, and to develop it up to the "level of acceptance" for common practice in industry. The observations and the existing modeling capabilities can be used to model the impact of the manufacturing process on contributing major sustainability parameters. Models developed for manufacturing variables can be integrated for achieving optimized performance. Finally, the optimized results can be used in defining the sustainability rating for the specific manufacturing process with appropriate weighing factors.

3.3 Sustainable Products from Sustainable Processes

As efforts continue to develop sustainable products and sustainable manufacturing processes, a recent trend observed is to develop sustainable products from sustainable processes, thus enabling, potentially, doubling environmental, economic and societal values of product manufacture. Case studies involving the use of sustainable machining methods such as dry, cryogenic and minimum quantity lubrication (MQL) machining have been shown for producing functionally superior machined products with significantly improved product sustainability, in terms of performance, quality and life [20]. Figure 5 shows a schematic of activities involved in producing sustainable products from sustainable processes.

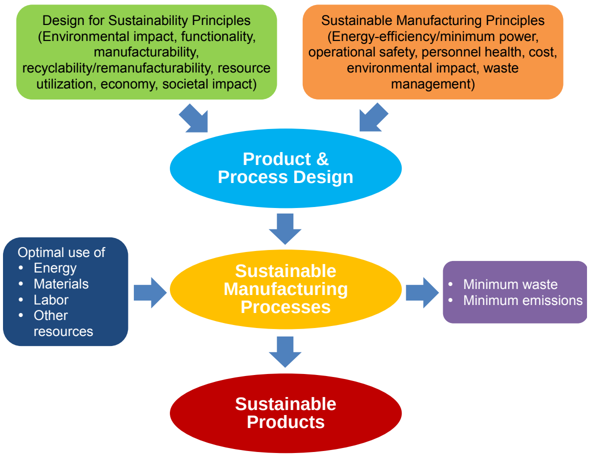


Figure 5: Proposed methodology for producing sustainable products from sustainable processes (Adapted from [20]).

3.4 Sustainability Issues at the Systems Level

The transformation of raw materials into more sustainable products through sustainable manufacturing processes requires careful coordination of various activities across and within the organizations that span the closed-loop supply chain. Historically, these supply chains have been designed and managed as open-loop systems aimed at coordinating the activities of independently managed organizations with the main emphasis being on maximizing profit [1]. From a systems perspective, developments in socio-technical systems theory [21] helped understand that manufacturing systems and support organizations are in effect technical systems embedded within social systems whose interactive complexities must be understood to manage these entities to achieve the desired performance.

However, for sustainability improvement, manufacturing system and supply chain design and operation must not only consider the behavior of the socio-technical system, but also integrate complexities of the interactions between the socio-technical systems and the natural environmental environment to minimize the unintended consequences. Also, systems are adaptive, and emergent entities [22] characterized by various feedback and reinforcing loops without a proper understanding of which can lead to catastrophic behaviors of these systems given the complex contexts in which they operate. Thus, sustainable manufacturing systems and supply chains must be designed and managed as integrated socio-techno-environmental systems from a total life-cycle perspective by considering the interfaces and interactions among the different sub-systems. Also, given the intractable nature of systems for sustainability, the ability to think and communicate systematically, or systems thinking, becomes an important capability that must be developed to increase the capability to design and manage such systems [21].

Given the above context, the design practices for sustainable manufacturing system and supply chain design must consider a variety of interactions between the methods and technical models, all the stakeholders who have an influence on the system or can be influenced by the system as well as the complex dependencies between these aspects and the natural environment. Evaluating the system performance from these aspects therefore will require comprehensive sustainability metrics at the plant, enterprise and supply chain levels; the adaptive and emergent behavior of the system designed with all other interactive systems, must be assessed through predictive models. The design protocol for designing such sustainable systems is shown in Figure 6.

Recent advances in sustainable supply chain design that follows some aspects of the approach shown in Figure 7 have addressed coordinating the design of sustainable products and systems by considering the social, economic and environmental implications of a variety of stakeholders; the time-variant, adaptive behavior of supply chains and implications on sustainability performance is also considered [24], [25]. Developing tools such as sustainable value stream mapping (Sus-VSM) to assess the socio-techno-environmental aspects at the manufacturing systems level have also been presented [26]. The modeling risks due to negative and unintended influences of economic, environmental and social implications from and on other inter-dependent systems (Figure 6) through probabilistic Bayesian Belief Networks can provide methods to develop mitigations/interventions to improve sustainability of manufacturing systems and supply chains [27].

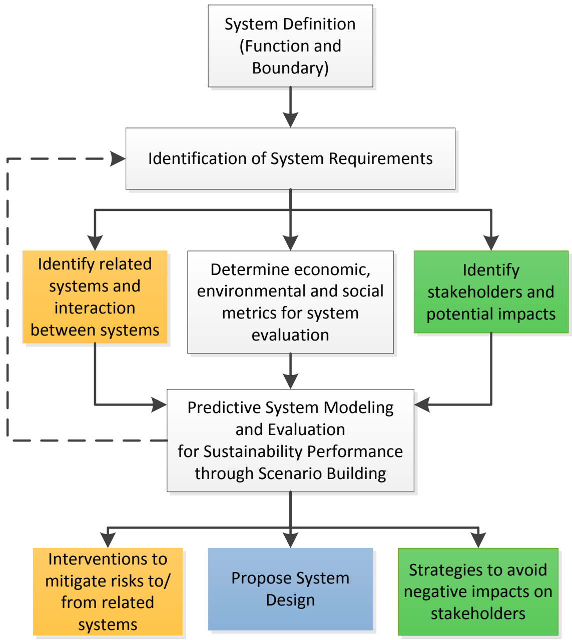


Figure 6: Protocol for Sustainable System Design (adapted from [23])

4 INNOVATIVE EDUCATIONAL PROGRAMS FOR SUSTAINABLE MANUFACTURING

Significant innovative content involved in sustainable manufacturing makes the education and training programs for next generation engineers and scientists challenging, and this should lead to new motivations for embarking on excellence in education and training programs. The International Framework for Action in Education developed following the initial discussions at the Rio Earth Summit in 1992, and further refined during subsequent gatherings, reiterates that, education must no longer be seen as an end, but the means to generate sustainable value. The need to disseminate knowledge skills and know-how to enable sustainable manufacturing as well as more sustainable consumption patterns are identified as one of the core-requirements for reorienting educational needs not only in developing countries, but also in developed regions of the world [29].

The new curriculum in sustainable manufacturing must be based on the strength of partnership among the three major participants: university, industry and state and federal organizations (Figure 8). The societal and environmental benefits, along with the economic gains, are achievable with this strategic partnership, which brings in education and training as the major linkage for these three units as shown in Figure 8. Traditional educational programs are generally evolved around the need for educating engineers and scientists the basic knowledge on physical and natural sciences, engineering materials, product design engineering and manufacturing sciences. These disciplines are taught in isolation and with no significant exposure to real world applications including social and human sciences.

The new curriculum will focus on multi-disciplinary, interconnected and environmentally and societally-relevant subjects knitted together to form the fabric of "sustainable manufacturing". Significant emphasis will be placed on developing new teaching and learning modules covering environment, economy and society, along with a thorough understanding of the natural cyclic systems representing the bio-complexity and reusable material bases including recyclability of materials. Design for sustainability principles will be taught to cover all relevant elements of practical sustainability focusing on the 6Rs (reduce, reuse, recycle, recover, redesign and remanufacture), and near-perpetual material flow from the closed loop approach involving four product life-cycle stages: pre-manufacturing, manufacturing, use and post-use. Also, the significance of marketing, innovation, management, ethics, regulations, policies, etc., will be covered in this proposed approach to provide a much broader knowledge base for next generation engineers and scientists who will learn science-based principles sustainability and will apply them to manufacturing. Also, manufacturing engineering science courses will include material on process performance enhancement, sustained quality, improved health and safety along with knowledge on cleaner manufacturing processes. The progression of cumulative learning at undergraduate and graduate levels extending up to PhD was shown in our prior work [17].

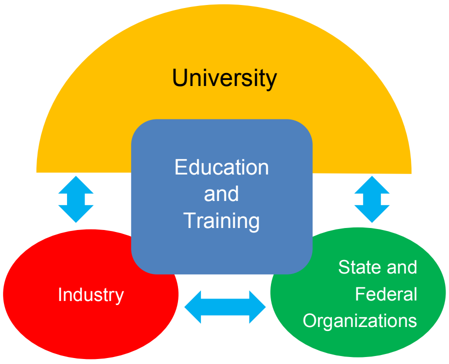


Figure 8: Integral role of university, industry and state and federal organizations in education and training (Adapted from [20]).

The proposed education and training program in sustainable manufacturing is an extended program beyond the traditional degree programs shown above. Identified five basic elements of this curriculum structure are: (a) new formal degree program based on instruction, lab work and projects at undergraduate and graduate levels, (b) a multi-disciplinary certificate program to provide a broader perspective on sustainability for engineers working in industry, (c) industry-relevant short courses, (d) professional/continuing educational programs, and (e) web-based online programs.

4.1 General background on strategic educational needs

Traditional product design and manufacturing methods are based on a range of product characteristics such as functionality, performance, cost, time-to-market, etc. Product design and manufacture in the 21st century will require a greater integration of life-cycle, sustainable product/process designs and their implementation in the manufacture of engineered products. This will apply to both consumer products in high volumes and small varieties and highly customized products in low volumes and large varieties. In particular, the design and manufacturing practices for next-generation products need to undergo major changes to include concerns that span the entirety of the traditional life-cycle, and ultimately from the perspective of multiple life-cycles/multi-uses involving perpetual material flow. Novel design methodologies, innovative manufacturing techniques, and effective tools must be developed to simultaneously address the total life-cycle issues including:

- Reduction of manufacturing costs
- Reduction of product development time
- Reduction of material use
- Reduction of energy consumption
- Reduction of industrial wastes
- Repair, reuse, recovery and recycling of used products/materials
- Environmental and societal concerns

This paradigm shift in product design and manufacture requires optimized methods incorporating environmentally conscious, energy-efficient, lean manufacturing methods with product maintenance, disassembly, material recovery, re-use, re-manufacturing and recycling considerations. It promotes a systems thinking in the design of new products and processes and calls for attention to the interests of all stakeholders. It requires devising new design methodologies, manufacturing processes, post-use processes, and enterprise resource planning in order to simultaneously achieve the multiple objectives of improving a company's profitability, bringing new products to market rapidly, conserving natural resources, while managing environmental concerns.

To enable sustainable products using sustainable processes, new capabilities to model and analyze complex interactions between various sub-systems at manufacturing system and supply chain level are required. Understanding and solving complex problems caused by the interactions between different aspects and stakeholders of the system to create sustainable value will require more intense cooperation between the various scientific disciplines as well as between the pure and social sciences [28]. This requires careful planning and a systematic development of new curriculum for implementation at all levels, beginning from high schools through to undergraduate and graduate programs. The following sections deal with topics that would make significant contributions to the proposed new educational programs.

4.2 Undergraduate education

One of the major concerns with undergraduate education is the increased compartmentalization of disciplines, which in the end produces graduates who are unable to view problems from any perspective other than taught in their own disciplines. All sustainability problems, including those in sustainable manufacturing involve complex issues, particularly at the systems level, that cannot be addressed by looking through the lens of one single discipline. Future engineers, scientists and managers must be taught skills and capabilities to view complex sustainability problems from different perspectives to enable robust solutions that are resilient to different externalities that may be encountered. However, the traditional model for undergraduate education in engineering and manufacturing has been highly discipline-specific, not providing the broad and well-rounded education needed to address sustainable manufacturing problems.

A recent unique effort in this area is an innovative team taught cross-disciplinary course for undergraduate students intended to transform science, technology, engineering and mathematics (STEM) education [29]. The course taught at the University of Kentucky brings together students and faculty from four different colleges—Engineering, Design & Architecture, Education and Business/Economics. In this course, titled ‘Systems Thinking for Sustainability, students are trained to address sustainability issues from a systems thinking perspective by using problem-based learning. From a teaching perspective, challenges identified through this experience will be relevant when transformative reforms to undergraduate sustainable manufacturing education are being planned.

4.3 Graduate education

For the most part, graduate education in sustainability studies has so far been limited to a focus on environmental technologies and business/management/leadership activities and programs mostly driven by popularity. Public awareness of the environmental effects of industrial production has largely been centered around programs that deliver courses aimed at assessing and managing the environmental impacts such as pollution studies, toxicity, public health and safety, waste minimization, emission studies, coolant reduction, restriction of the use of chemicals, product and process quality studies, reliability, monitoring and maintenance of machinery and equipment, etc. Sustainable manufacturing education at the graduate level must have a much broader emphasis not just limited to environmental aspects but integrating social aspects and covering product, process and system to advanced capabilities to model, evaluate and analyze these three elements to advance sustainability.

4.4 Professional development and continuing education/training

Industry-based practicing engineers and professionals seek to pursue continuing educational programs in an effort to update their knowledge with recent advances and future developments. Short courses, workshops and professional development programs on dedicated topics organized and delivered by academic institutions, professional societies and other consulting groups help to achieve targets for such professionals, often with full sponsorship by their employers. Also, signature conference series sometimes offer such programs as add-on components. A range of topics covered by such programs focusing on sustainable manufacturing has in recent times been elevated to be among the most popular programs as the employers continue to recognize the economic impact of implementing sustainable manufacturing for their products and processes.

4.5 Other educational needs

As pointed out by many, ‘basic education provides the foundation for all future education and learning’ [28]. Thus, to derive effective outcomes from the transformational reforms to undergraduate, graduate and professional education for sustainable manufacturing in the long run, the ‘seeds’ of knowledge and the value system to appreciate the importance of sustainability in general, as well as sustainable production and also the importance of more responsible behavior and sustainable consumption, must be developed at an early age [28]. As such, educational reforms to increase innovative capabilities through sustainable manufacturing must begin even earlier, possibly at the pre-kindergarten level and continue through K through 12 levels; such a broad approach will help transform the mental models of the future workforce to effectively participate in shaping a sustainable future through sustainable value creation.

5 CONCLUSIONS

Innovative sustainable manufacturing can become the engine for sustainable growth by not only promoting economic growth, but also enabling social well-being and environmentally conscious practices. Creating value through sustainable manufacturing will require innovation at the product, process and systems levels across the total life-cycle and through multiple life-cycles. The complex challenges that must be balanced when promoting sustainable manufacturing at these different levels will necessitate the future generation of engineers, scientists and managers who have the required education and training to address these challenges for sustainable value creation. While important strides have been made in reviving the educational curricula to meet some of these needs, there are still significant reforms necessary to develop multi-disciplinary and cross-cutting educational programs that will also transcend the traditional boundaries between disciplines. New models for sustainable manufacturing education must aim to change the mindsets of future generations beginning at an early age then fostered through formal education at undergraduate, graduate and professional levels. Further, with an increasingly web-savvy future generation, there is also a need to extend the dissemination of such educational programs through new mechanisms such as on-line degree programs.

REFERENCES

[1] Jayal, A.D., Badurdeen, F., Dillon Jr., O.W., Jawahir, I.S., 2010, Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels, CIRP Journal of Manufacturing Science and Technology, 2: 144-152.

[2] Jawahir, I.S., Rouch, K.E., Dillon, O.W., Jr., Joshi, K.J., Venkatachalam, A., Jaafar, I.H., 2006, Total life-cycle considerations in product design for manufacture: A framework for comprehensive evaluation, (Keynote Paper), Proc. TMT 2006, Lloret de Mar, Barcelona, Spain, 1-10.

[3] Jawahir, I.S., O.W. Dillon, Jr., 2007, Sustainable manufacturing processes: New challenges for developing predictive models and optimization techniques, (Keynote Paper), Proc. 1st International Conference on Sustainable Manufacturing (SM1), Montreal, Canada, 1-19.

[4] Badurdeen, F., Goldsby, T.J., Iyengar, D., Metta, H., Gupta, S., Jawahir, I.S., 2010, Extending Total Life-cycle Thinking to Sustainable Supply Chain Design, International Journal of Product Lifecycle Management, 4/1/2/3: 49–67.

[5] Nidumolu, R., Prahalad, C.K., Rangaswami, M.R., 2009, Why sustainability is now the key driver of innovation, Harvard Business Review September 2009, 3-10.

[6] Kiron, D., Kruschwitz, N., Haanaes, K., Reeves, M., Goh, E., 2013, The innovation bottom line, MIT Sloan Management Review Research Report Winter 2013.

[7] Ueda, K., Takenaka, T., Vancza, J. and Monostori, L., 2009, Value creation and deicision making in sustainable society, CIRP Annals – Manufacturing Technology, 58/2: 681-700.

[8] Sutherland, J.W., Kumar, V., Crittenden, J.C., Durfee, M.H., Gershenson, J.K., Gorman, H., Hokanson, D.R., Hutzler, N.J., Michalek, D.J., Mihelcic, J.R., Shonnard, D.R., Solomon, B.D., Sorby, S., 2003, An education program in support of a sustainable future, Proceedings of ASME-IMECE November 16-21, 2003.

[9] Jovane, F., Yoshikawa, H., Alting, L., Boër, C.R., Westkämper, E., Williams, D., Tseng, M., Seliger, G., Paci, A.M., 2008, The incoming global technological and industrial revolution towards compressive sustainable manufacturing, CIRP Annals-Manufacturing Technology, 57: 641-659.

[10] Evans, S., Bergendahl, N., Gregory, M., Ryan, C., 2008, Towards a sustainable industrial system, University of Cambridge, Institute for Manufacturing, Department of Engineering, www.ifm.eng.cam.ac.uk.

[11] Davidson, C.I., Hendrickson, C.T., Matthews, H.S., Bridges, M.W., Allen, D.T., Murphy, C.F., Allenby, B.R., Crittenden, J.C., Austin, S., 2010, Preparing future engineers for challenges of the 21st century: Sustainable engineering, Journal of cleaner production, 18/7: 698-701.

[12] Murphy, C.F., Allen, D., Allenby, B., Crittenden, J., Davidson, C.I., Hendrickson, C., Matthews, H.S., 2009, Sustainability in engineering education and research at U.S. universities, Environ. Sci. Technol, 43/15: 5558-5564.

[13] Allenby, B., Murphy, C.F., Allen, D., Davidson, C., 2009, Sustainable engineering education in the United States, Sustain Sci, 4: 7-15.

[14] Rochon, G.L., Nies, L.F., Jafvert, C.T., Stuart, J.A., Mohtar, R.H., Quansah, J., Martin, A., 2006, Education in sustainable production in US universities, Clean Techn Environ Policy, 8: 38-48.

[15] Ferrer-Balas, D., Adachi, J., Banas, S., Davidson, C.I., Hoshikeshi, A., Mishra, A., Motodoa, Y., Onga, M., Ostwald, M., 2008, An international comparative analysis of sustainability transformation across seven universities, International Journal of Sustainability in Higher Education, 9/3: 295-316.

[16] Huntzinger, D.N., Hutchins, M.J., Gierke, J.S., Sutherland, J.W., 2007, Enabling sustainable thinking in undergraduate engineering education, Int. J. Engng Ed., 23/2: 218-230.

[17] Jawahir, I.S., Rouch, K.E., Dillon Jr., O.W., Holloway, L., Hall, A., 2007, Design for sustainability (DFS): new challenges in developing and implementing a curriculum for next generation design and manufacturing engineers, Int. J. Engng Ed, 0/0: 1-12.

[18] Haapala, K.R., Zhao, F., Camelio, J., Sutherland, J.W., Skerlos, S.J., Dornfeld, D.A., Jawahir, I.S., Clarens, A.F., Rickli, J.L., 2013, A review of engineering research in sustainable manufacturing, Journal of Manufacturing Science and Engineering, 135: 041013-1 to 041013-16, ASME (To appear).

[19] Graedel, T.E., 1998, Streamlined life-cycle assessment, Prentice-Hall, New Jersey, USA.

[20] Badurdeen, F., Jayal, A.D., Jawahir, I.S., 2009, Towards a System Approach for Developing Sustainable Products from Sustainable Manufacturing, Bangalore Workshop, Bangalore India.

[21] Soderquist, C. and Overakker, S., 2010, Education for Sustainable Development: A Systems Thinking Approach, Global Env. Research, 14: 193-202.

[22] Hughes, T. 1989, The Evolution of Large Technical Systems, In Bijker W. and Hughes, T. and Pinch, T. (eds.), The Social Construction of Technological Systems: MIT Press, Cambridge, MA: 51-87.

[23] Fiksel, J., 2003, Designing Resilient, Sustainable Systems, Environmental Science and Technology, 37: 5330-5339.

[24] Metta, H. and Badurdeen, F. 2011, Sustainable Supply Chain Design: Optimization and Multi Life-cycle Analysis, Pro. of 44th CIRP Conference on Mfg. Systems, Madison, WI.

[25] Metta, H. and Badurdeen, F., 2013, Integrating Sustainable Product and Supply Chain Design: Modeling Issues and Challenges, 60/2:438-446.

[26] Faulkner, W., and Badurdeen, F., 2012, Visualizing Sustainability Performance of Manufacturing Systems using Sustainable Value Stream Mapping (Sus-VSM), Pro. of International Conference on Industrial Engineering & Operations Management, Istanbul, Turkey.

[27] Badurdeen, F., Shuaib, M., Wijekoon, K., Brown, A., Faulkner, W., Amundson, J., Jawahir, I.S., Goldsby, T. J., Iyengar, D. and Boden, B., 2013, Quantitative Modeling and Analysis of Supply Chain Risks using Bayesian Theory, Journal of Manufacturing Technology Management, In Press.

[28] UN Report, 1997, United Nations Educational, Scientific and Cultural Organization: Educating for a Sustainable Future – A Transdisciplinary Vision for Concerted Action.

[29] Badurdeen, F., Brown, A., Gregory, R., Fu, H., Schroeder, M., Sekulic, D., Vincent, L. and Luhan, G.A., 2013, Reframing Interdisciplinary Approaches to Systems Thinking for Sustainability, Proceedings of the International Symposium on Sustainable Systems & Technologies, May 15-17, 2013, Cincinnati, OH

Sustainability in manufacturing with a perspective on UAE / Masdar

Marwan Khraisheh

Masdar Institute of Science and Technology, Abu Dhabi, UAE

Abstract

The UAE, similar to other countries in the Middle East, is embarking on an ambitious journey to transform its economy from one based on natural resources to a diversified one based on knowledge and innovation. The transformation will rely on expanding and developing new sectors as engines for economic growth. Manufacturing and Sustainability will play an important part in this transformation. In this talk, an overview of UAE's vision will be presented with a focus on the manufacturing sector. Additionally, the government has established Masdar Institute as a graduate level, research driven university focused on sustainable technologies. An overview of educational and research activities relevant to sustainable manufacturing will be presented.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

Sustainable manufacturing - German perspectives on shaping global value creation

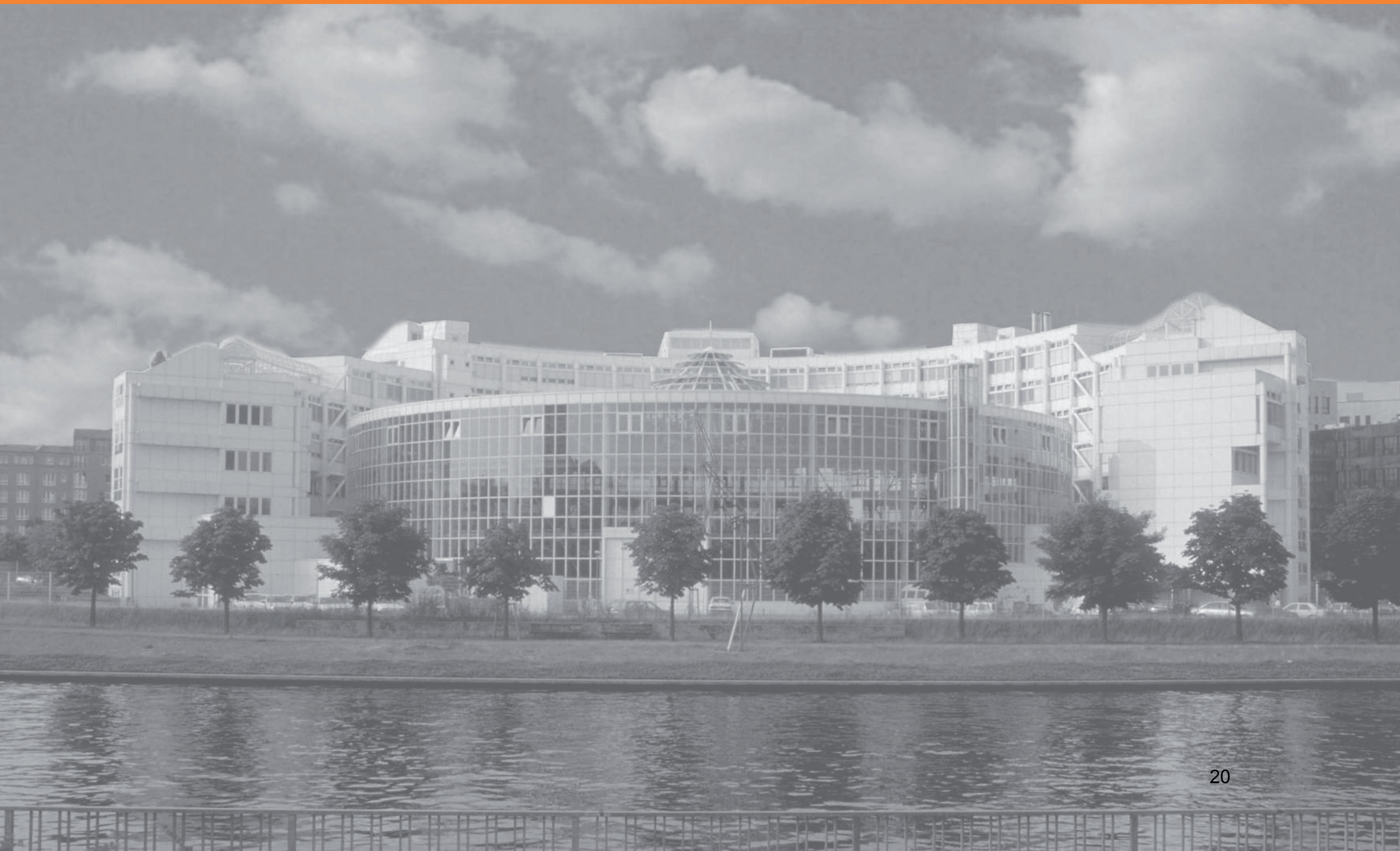
Günther Seliger
Technische Universität Berlin, Germany

Abstract

With the continuous depletion of natural resources along with the incremental increase in world population, the need for effective and economic use of renewable resources becomes significant. Innovative solutions for sustainable manufacturing should be initiated to cope with the challenges of economic competitiveness, environmental and social stability. Collaborative Research Centre "Sustainable Manufacturing – Shaping Global Value Creation" (CRC 1026) intends to demonstrate how sustainable manufacturing is embedded in global value creation. Products, processes, equipment, organization and humans together as configurable factors constitute creating modules. Modules to be shaped by innovative technology are valuated according to economic, environmental and social criteria of sustainability. Vertical and horizontal integration driven by cooperation and competition leads to value creating modules connected in dynamic networking. Manufacturing and logistics in their fundamental roles for wealth generation considerably shape these networks. First results of CRC 1026 are presented.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

Session 1
Entrepreneurship



GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

1.1 Sustainability incubators: A coordinated collaborative approach towards sustainable manufacturing amongst small and medium-sized enterprises.

H. Kohl[1], R. Orth[1], M. Galeitzke[1]
[1] Division Corporate Management, Fraunhofer IPK Berlin, Germany

Abstract
Small and medium-sized enterprises constitute a major share of the manufacturing sector in many countries and are known for their dynamic structure and innovative strength. Despite the potential for sustainability performance the economic impact of environmental regulations may impede many business ventures. Business incubators foster entrepreneurship by offering infrastructural facilities and legal support. The central management of environmental impact reduction and cross-application technologies can in some cases be profitable. The entrepreneurial framework may initiate progress towards the application of sustainability principles. Benchmarking as a powerful management tool can induce best practice transfer and the conceivable collaborations may generate eco-innovations, social and creatively beneficial environments as well as economic advantages. The induced performance measurement, comparison and exchange of experiences is directed towards collective sustainability performance.
Keywords:
Business incubators, sustainability, sustainable manufacturing, ecologic innovations, manufacturing networks, Benchmarking

1 INTRODUCTION

The concept of sustainable development has progressed from a political discussion towards a formal commercial performance model and combines the requirements of politics, society and entrepreneurs as well as economic share- and stakeholders. While the ecologic perspective of sustainability is the most formalized research topic within this model, the social and economic determination factors have gained importance and scientific attention. The number of analysis and management tools that attempt to integrate the principles of sustainability into the daily business operations has multiplied accordingly. However, the complexity of the interaction between industrial production and the economic, social and ecologic environment and the necessary manageability of such tools stands in sharp contrast. In some use-cases this may lead to an impaired perception of the necessary sustainability performance of enterprises. The sustainability performance aggregates the result of sustainable management, which is associated with the measurement and evaluation of performance indicators [1]. The exploitation and usage of natural resources, the environmental pollution and social impact of industrial production are very significant determining factors for the necessity of the individual and collective implementation of sustainable manufacturing. The manufacturing sectors of many countries however, are composed of a majority of small and medium-sized enterprises (SME) and smaller numbers of large enterprises. These small and medium-sized enterprises face certain difficulties and restricting factors in regard to the implementation of sustainable manufacturing concepts. This paper designs an application-oriented concept towards sustainable manufacturing amongst small and medium-sized enterprises through a coordinated and collaborative approach.

2 THE CONCEPT OF SUSTAINABLE MANUFACTURING

In order to develop the coordinated collaborative approach towards sustainable manufacturing amongst small and medium-sized enterprises, the following will provide a short overview of the main underlying concepts of sustainable manufacturing. In addition, the determination factors of manufacturing enterprises and the particularities of small and medium-sized enterprises are outlined to denote the application-oriented theme of the concept.

2.1 Sustainability of manufacturing activities

The determination and progression of sustainability performance in manufacturing enterprises has been the focal point of many recent publications and scientific events. The fundamental idea of the substantial potential contribution to sustainable development by the manufacturing sectors [2] is adapted as the basis of the further elaboration. The main understanding of sustainable manufacturing is based on the transmission of the triangle of tension of sustainability to manufacturing activities, wherein the three perspectives (economic, ecologic and social sustainability) are expanded by five basic strategies [3]. These strategies simultaneously complement the model of sustainability and elaborate on the interdependencies between the perspectives. Figure 1 shows the triangle of tension with the three perspectives supplemented by the socio-effectiveness, socio-efficiency, eco-efficiency, eco-effectiveness, sufficiency and ecologic justice strategy.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

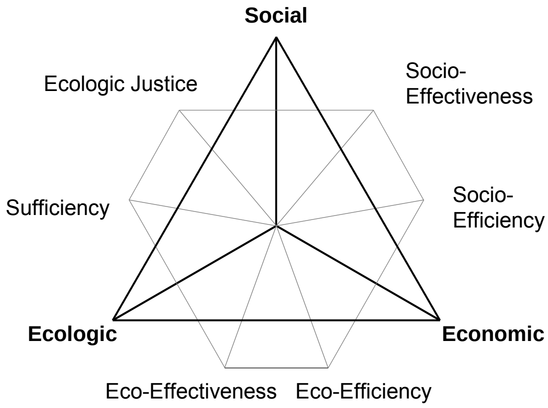


Figure 1 : Tension triangle of sustainability, modeled after [3]

The expansion of this concept across the borders of the individual production systems is on the one hand an imperative, as the sustainability performance of any enterprise is rendered mute if the subcontractors counteract the sustainability of the corresponding product. On the other hand it is seems rather complicated to control the conduct of other enterprises even if they are part of the immediate value chain.

Based on the described tension triangle of sustainability, the determination factors of manufacturing enterprises can be summarized to a standardized set of cause-effect relationships. From these, the principles and strategies can be transformed into directives for sustainable manufacturing, when taking into account the internal and external stakeholders. The directives aim at enabling the implementation of systems and processes that are “non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for workers, communities, and consumers, and socially and creatively rewarding” [4]. From a systems-theory perspective, cause-effect relationships are possible within and between the three perspectives of sustainability. These dependencies and interactions can have either a positive, negative or neutral impact on the underlying objective of preserving the ecological, economic and social environment. Furthermore, these can be categorized by location, time and reflexivity [5]. Thus, interactions may occur within the considered systems or across the system boundaries to influence other systems. Simultaneous or delayed interactions are often difficult to identify because the simultaneous influence may be misinterpreted as independent or latent interactions are not detected. Such interactions may have the characteristic of being reinforcing, respectively debilitating mechanisms or actions. The measurement, evaluation of cause-effect relationships and determination factors and the definition of activities or actions that specifically deal with these are the challenge of the operative management of sustainability performance.

2.2 Particularities of manufacturing SME

Small and medium-sized enterprises evidence certain particularities in terms of the implementation capabilities of actions that increase the sustainability performance. As the competitive situation on the globalized market has tightened, the financial scope for action has notably decreased for most enterprises. As activities that actively deal with determination factors of manufacturing enterprises are associated with additional costs for the enterprises, the demonstration of the direct benefit of these activities is of high significance in this context. While economic impact is the most direct to be measured, it is the performance of enterprises directed towards the improvement of the environmental and social impact that is of interest to the public and regulating authorities. The aforementioned problematic cross-enterprise responsibility is underlined when considering the economic influence of a single small or medium sized enterprise. The supplier-consumer relationship in this case does not necessarily allow an extensive requirements profile, as the quantities of economic transaction of individual SME fall into insignificance to some suppliers.

2.3 Concernment of enterprises

It has been argued, that the concernment of small and medium-sized enterprises in regard to legal requirements is likely to be much lower than that of large enterprises [6]. This argument is based on the limited capacity of regulation authorities, which prevents the thorough enforcement of regulations in all enterprises of the corresponding domain. Meanwhile, the imposed regulations are mostly concerned with or complied with downstream or additive technologies that reduce environmental or social impact. Therefore, the influence of regulations and legal requirements is not likely a driver for a holistic progression of sustainable manufacturing.

While large enterprises are in fact faced with an arguably higher concernment in terms of environmental, social or economic requirements and regulations, they are additionally exposed to the public on a much larger scale. This implicates further requirements by stakeholders and the public as sustainability has also transformed to a rather publicity effective topic in the positive but also negative sense.

2.4 Towards sustainable manufacturing

The limited concernment of small and medium-sized enterprises and the restricted exposure to the public are factors that may hinder the active increase of the individual sustainability performance. Furthermore, the limited scope for actions of SME may be misinterpreted as an inability to act, which would neglect the principle concept of sustainability to preserve the operability of the own enterprise as part of the intra- and inter-generational responsibility and fairness.

It is the private organizations’ responsibility to shape the future actively and incorporate sustainability not only as a concept but as an imperative policy to their operation. This directly induces the disentanglement from sustainable development barriers as for example the concernment of enterprises in terms of regulations and the exposure to the public. The progression of this development needs to be actively driven by the private sector enterprises as potential and resources to foster sustainable development are anchored within these structures.

Sustainable manufacturing can also be interpreted as an opportunity rather than a challenge. The integration of one’s own enterprise to the a new market that demands sustainable products and codes of conduct may be a potential source of new or increased sources of revenue adding to the possible savings of increased efficiency [7]. Further opportunities of sustainable manufacturing can be categorized by the involved stakeholders and the three perspectives of sustainability [1].

This brings the responsibility of the individual enterprise to the focus of attention, as a possible misconduct is assumed.

3 COLLABORATIVE SUSTAINABILITY

The collaboration of small and medium-sized enterprises can be considered separately with regard to the collaboration within networks and along value chains. The collaboration of SME in networks, as those being discussed within this concept, is likely to develop if the participating enterprises benefit from such activities. The collaboration along value chains in terms of sustainable manufacturing may be requirement-driven, as the responsibility of enterprises is not limited to the individual organizational unit but extends across the downstream value-chain.

3.1 Sustainable manufacturing in SME networks

The collaboration of enterprises in networks that are not necessarily bound in the compound structure of a purchaser-supplier relationship (see 3.2) is increasingly becoming the basis for innovation and lasting business success. The management of sustainability performance is herein a substantial part of the cross-company cooperation strategies that tend to form due to the increasing competitive challenges [8]. Enterprises are moreover faced with challenges induced by changing framework conditions and structures of the markets. In retrospect the increasing economic pressure due to increasing competition and product variants, parallel to decreasing liquidity of enterprises as well as the scarcity of resources [9] of the past decade has escalated this situation.

Many of the existing management approaches to sustainable development or specifically sustainable manufacturing revolve around the ecologic perspective, as the determination factors are sufficiently described through the technological processes. The efficiency of these processes and the reduction of environmental impact are emphasized. However, these approaches only focus on the individual enterprise, while the true strength of such activities that increase efficiency and reduce environmental impact has to be attributed to the collaboration in networks. Sharing tangible resources within networks organizations may increase efficiency and business opportunities for all participants, since the optimal use of capacities and technological capabilities is enabled. The collaboration in terms of the reduction of environmental impact as well as the increase of technological capabilities is driven by the sharing of tangible resources. To some extent the collaboration may in fact have positive effects on more than one perspective of sustainability. The identification and avoidance of environmental impact of cross-application technologies has a significant economic impact to the operation of individual enterprises. This effect may be exploited on a larger scale in networks of enterprises relying on the same or similar technologies.

Intangible assets however, are essential success factors for enterprises and to some extent determine the effectiveness of the previously discussed collaboration potential. The intellectual capital of an organization – categorized into the human capital, structural capital and relation capital [10], [11] – in an inter-organizational exchange can be assessed as an alternative reason for the formation of enterprise networks [12]. While the concept of inter-organizational collaboration regarding intellectual capital is relatively new [13], some efforts have been taken to incorporate sustainability into knowledge management systems [14]. The entire organizational structure requires sustainability knowledge in regard to the corresponding processes in order to implement the sustainability strategies [15].

Based on the model of cooperation (Figure 2) the interfaces of collaboration could be assessed in regard to the assessment of social, environmental and economic impact along with the integration of knowledge management systems in network organisations.

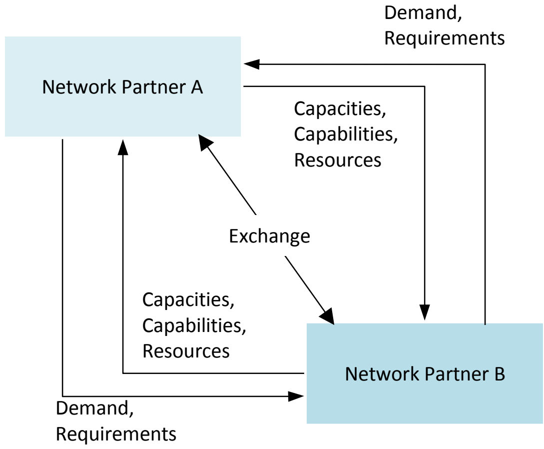


Figure 2: Basic Model of Cooperation, modeled after [16]

3.2 Sustainable manufacturing along value-chains

The labor division among SME along value-chains, which may be induced by the specialization on core competencies and therefore the decrease of depth of the value added of the individual enterprise, presents a special form of network collaboration. The basic collaboration is manifested in the transmission of requirements in terms of technical specifications within the manufacturing process (Figure 3).

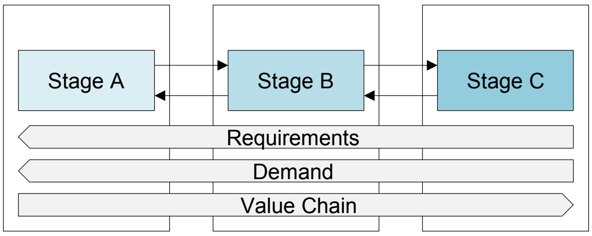


Figure 3: Collaboration along value-chains.

The technical requirements and production quantities are specified in the respective subsequent stage of production – in a single stage model of value-chains this is represented by the industrial consumer. If the principle of responsibility beyond the individual enterprise boundaries is adopted, these requirements can also include parts of the sustainability objectives of the subsequent enterprises. However, an insignificant economic influence may limit this influence if not considered on a broader scale. If a critical mass of enterprises adopts the requirements that go beyond technical specifications and integrate sustainability principles to the selection of suppliers, the demand-driven sustainability performance of suppliers may increase.

4 COORDINATING SUSTAINABLE MANUFACTURING

Business incubators and technology or innovation parks have proven to be a nurturing environment for enterprises of similar industry affiliations and especially equal or similar value-chains. Specifically small and medium-sized enterprises may benefit from the infrastructure and organizational services offered by such entities. One particular concept of a business incubator is to support the affiliated enterprises by offering adapted and favorable framework conditions. The following chapters will incorporate the sustainability perspectives and strategies into the coordination of enterprises within an assumed network independently of the cause of its development.

4.1 Business incubators as the coordinating pioneer

The coordinating functions of the business incubators are herein focused on enabling the discussed collaborative sustainability as well as individual sustainability performance of the affiliated enterprises. Therefore, the business incubators may act as a coordinating pioneer, as the enterprises are supported in adapting sustainable manufacturing and are encouraged through possible good practices by other enterprises in this environment. Provided that the sustainability performance is measurable and existent in the individual enterprises, the business incubator may in fact impose own regulations and specifications that specify requirements for the performance of the enterprises. Thereby, the business incubator further enhances the sustainability performance of the enterprises, which may in turn lead to a certain added value for the enterprises through reputation.

4.2 Central management for sustainability performance

The operational objective of a sustainability incubator is to provide the enterprises with the framework that enables the increase of sustainability performance. The organizational structure of business incubators allows the central management of determination factors, which can improve the efficiency of the processes involved by utilizing scale effects. These management support services need to be regarded as optional as the provision is associated with costs that have to be re-distributed to the enterprises. However, the framework of such a business incubator and the enterprises within are construed on the assumption that the centralized support will be accepted.

The framework that is to be provided applies to the entire production system (Figure 4). The provision of factory and office space at favorable conditions is the initial service provided in this regard, as the ramp-up phase of manufacturing SME relies on the operability of the production system. On the input side of this system the enterprises may benefit of a centralized purchasing unit. Thus, parts of the relational capital of the enterprises are combined to a network resource. Further beneficial framework conditions may be provided through a sustainability intelligence system that serves as an adapted knowledge management system.

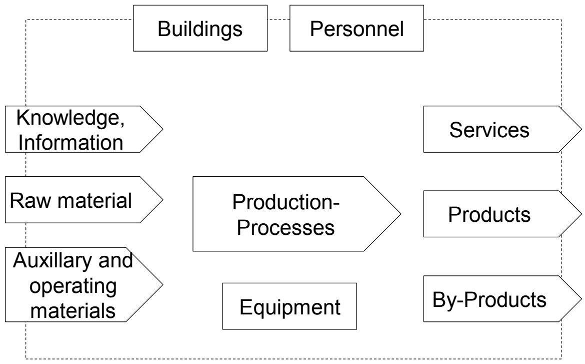


Figure 4 : Production-System modeled after [17]

Information on codes of conduct and regulations regarding the ecological and social environment can be gathered and provided, whereas the insights to technological design options of manufacturing processes can only be provided if the participating enterprises share this knowledge with their peers. Assuming that the willingness to share information is provided, the enterprises may form innovative networks, where the provided information is utilized to generate new solutions for the avoidance or reduction of environmental or social impact. The dissemination of the generated knowledge within the network is provided through the knowledge management system and may be further spread beyond the boundaries of this system, provided that it is not an essential competitive advantage.

The coordination of the cross-enterprise utilization of infrastructure and equipment may on the one hand enable enterprises to expand their production and create further added value. On the other hand, the enterprise that is allowing the utilization of its own equipment can benefit from an increased load factor. The network as a whole is thereby increasing its efficiency, simply by sharing and utilizing un-used equipment-time. Thus, the single production systems' boundaries are partly dissolved and a network production system is formed, which utilizes network resources in terms of technological equipment as well as sharable resources in terms of the intellectual capital (Figure 5).

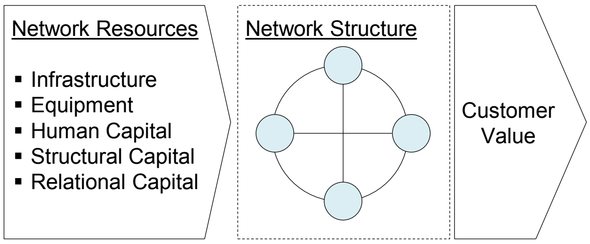


Figure 5 : Network production system.

Downstream and additive technologies to reduce environmental impact can be shared in order to increase the effectiveness and efficiency of these systems. For instance the centralized waste heat utilization, waste water and exhaust treatment may induce monetary savings through scale effects and increase the effectiveness of these technologies.

4.3 Monitoring and management of sustainability performance

The following gives an evaluation of approaches to the monitoring and subsequent management of the sustainability performance of the sustainability incubator with regard to the structure and peculiarities of the enclosed enterprises.

The monitoring – and reporting – of the sustainability performance could follow established systematic approaches such as the reporting guidelines of the *Global Reporting Initiative (GRI)*. However the incremental reporting in accordance with the GRI framework, as a baseline approach for reporting enterprises [18] may account for an inhomogeneous reporting of the incubator – due to the particularities and differences in maturity of the enterprises. Thus, the centralized management of the sustainability performance would only create a distorted snapshot of individual Key Performance indicators.

Considering the intended purpose of an incubator it is herein proposed to develop a predefined set of target domains in which the enterprises define individual qualitative targets and measure qualitative achievement values. In accordance to the tension triangle of sustainability (Figure 1) the following systematic describes an approach to the definition of individual strategic targets within a common structure. The overall performance of the sustainability incubator, as the sum of individual performances is apriori limited by the data collection of the individual enterprises. However, the coordinated definition of targets within the predefined domains may on the one hand create a common reporting framework within the hemisphere of the sustainability incubator. On the other hand it may well be beneficial to the individual enterprise as it induces the process of defining targets that have beneficial effects in all perspectives.

If the sustainability performance monitoring is construed in a consistent, uni-directoinal manner – either burden-oriented or reduction-oriented – and consist of homogeneous target dimensions then the comparison of the individual sustainability performance against that of the business incubator as a virtual organization allows the identification of performance gaps.

Figure 6 shows a generic model of an intra-network comparison of sustainability performance in accordance with the tension triangle of sustainability.

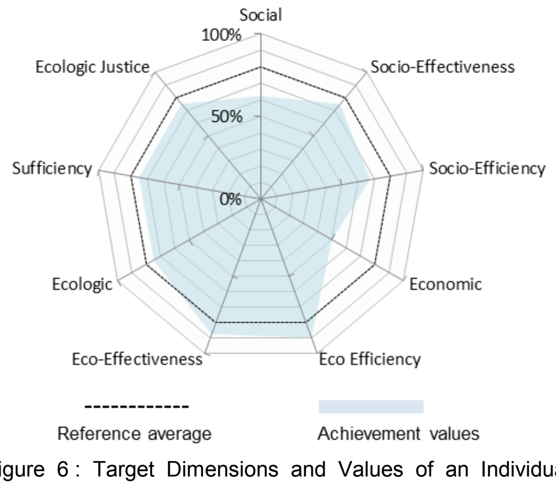


Figure 6 : Target Dimensions and Values of an Individual enterprise within the Incubator Framework

The thereby created monitoring of qualitative target achievement in combination with the coordinating function creates the possibility of intervention or control of improvement and incorporates a network or Incubator governance, with self-imposed targets.

4.4 Benchmarking sustainability performance

As discussed the systematic management of sustainability performance is an essential aspect of the operability and implementation of sustainability strategies within manufacturing enterprises. A significant problematic aspect of sustainability performance of manufacturing enterprises - if considered detached from legal regulations or requirements - is the definition of the necessary level of sustainability performance. If a development process is assumed that will shape the informal requirements of the concept of sustainable manufacturing, a basis for the improvement of sustainability performance needs to be defined. Differentiated Benchmarking-applications for the activities of the individual organizational structure levels provide management tools to integrate the directives and strategies to the different management levels of the enterprises [19]. Yet the operation of the individual enterprise is significantly responsible for the level of sustainability performance. The classical approach of identifying potentials for improvement across the enterprises structure [20] may be transformed into a continuous process to increase sustainability performance.

A fundamental yet challenging approach to define a basis for the measurement and comparison on the operational level is to develop reference values of certain key performance indicators. The comparison of the individual enterprises in regard to these reference values immediately gives an estimate of the potential surplus or deficit of sustainability performance. The BenchmarkIndex™ as described in its sustainable procedure may enable manufacturing SME to improve their economic performance and simultaneously measure and compare innovative key performance indicators that allow statements on the ecologic and social performance [21]. At the same time the described discrepancy between the actual and aspired level of sustainability performance may be solved.

5 CONCLUSION AND OUTLOOK

Combining the strength of small and medium-sized enterprises to operate and innovate in networks and the guidance of a sustainability incubator is an application-oriented solution to the described mission to progress the sustainable development from the private sector. The beneficial framework conditions for the enterprise network and the direction predetermined by the objective of the sustainability incubator are an initial step towards this imperative. Supporting the small and medium-sized enterprises of the manufacturing sector is an essential economic policy to underline the sustainable development of almost any economy. The provision of education, employment and economic added value are substantial contributions of these enterprises.

The knowledge of the enterprises and thereby the capabilities of the personnel within the network are utilized to create services and products in an effective and efficient way enabling the increase of sustainability performance of the individual enterprises. The strong and innovative network that is coordinated by the sustainability incubator benefits of the systematic management of the success factors and their utilization and gains potential to increase its innovation activities in regard to environmental and social determination factors.

The division corporate management of the Fraunhofer Institute for Production Systems and Design Technology (IPK) has gathered experience in both the provision of knowledge management solutions as well as the research regarding knowledge management in networks to increase sustainability. Furthermore the development of new methodologies for the measurement and evaluation of the sustainability performance of SME is an essential aspect of its research and development activities [22]. As part of the future research, a case study with a network of collaborating SMEs is intended that utilizes the learning about small scale enterprises and incubators, the strategic and implementation planning of science and technology parks as well as the comprehensive understanding of national innovation systems [23].

6 ACKNOWLEDGEMENT

The results are part of the ongoing research project “Sustainable Manufacturing – Shaping global Value Creation”. The project is funded by the German Research Foundation DFG.

[1] VDI Richtlinie 4070, 2006, Sustainable management in small and medium-sized enterprises. Guidance notes for sustainable management. Verein Deutscher Ingenieure. Beuth-Verlag, Düsseldorf.

[2] OECD, 2009: Eco-Innovation in Industry: Enabling green growth. Organization for economic co-operation and development.

[3] Dyllick, T., Hockerts, K. 2002. Beyond the Business Case for Corporate Sustainability. In Business Strategy and the Environment. Vol. 11, 2002, S. 130-141. Wiley and Sons, Ltd and ERP Environment.

[4] Nasr, N., Thurston, M. (2006): Remanufacturing: A key enabler to sustainable Product systems. Proceedings to the 13th International Conference on Life Cycle Engineering. Katholieke Publishing, Leuven.

[5] Gleich, A., v., Gößling-Reisemann, S., 2008, Industrial Ecology: erforlgreiche Wege zu nachhaltigen industriellen Systemen, Vieweg + Teubner Verlag, Wiesbaden.

[6] Baum, H.-G., Albrecht, T., Raffler, D., 2007, Umwelt- und Ressourcenschutz als Unernehmensziel: Steigerung des Unternehmenswerts durch Ressourcen-management. Deutscher Universitätsverlag, Wies-baden.

[7] OECD, 2011, Sustainable Manufacturing Toolkit. Seven Steps to Environmental Excellence. www.oecd.org/innovation/green/toolkit

[8] Sydow, J. (Ed.) 2001, Management von Netzwerkorganisationen – Beiträge aus der Managementforschung, Gabler Verlag, Wiesbaden.

[9] Heimig, J., Quick, J., Weinholdt, H., Bronze, T. Sustainable Corporation in Networks – Evaluating the Sustainable Implementation of Logistic Concepts in Networks, In: Seliger, G. et.al. (Eds.), Advances in Sustainable Manufacturing: Proceedings of the 9th Global Conference of Sustainable Manufacturing. Springer Verlag, Berlin, 2011.

[10] Sveiby, K.E., 1997, The New Organizational Wealth – Managing and Measuring Knowledge Based Assets, Berret-Köhler, San Francisco.

[11] Edvinsson, L., Malone, 1997, Intellectual Capital, Harper, New York.

[12] Wildemann, H., 2000, Wissensmanagement – Dargestellt am Beispiel von Entwicklungsnetzwerken. In: Krallmann, H.(Ed.), Wettbewerbsvorteile durch Wissensmanagement, pp. 53-69, Stuttgart.

[13] Weissenberger-Eibl, M., 2006, Wissensmanagement in Unternehmensnetzwerken, Cactus Verlag, Kassel.

[14] Posch, A., Perl, E., 2005, Industrielle Nachhaltigkeitsnetzwerke – Ein praxisorientierter Leitfaden. Bundesministerium für Verkehr, Innovation und Technologie, Vienna.

[15] Al-Laham, 2008, Strategische Aspekte von Nachhaltigkeit am Beispiel des Managements von Unternehmensnetzwerken. In: von Hauff, M., Lingau, V., Zink, K.J., (Eds.): Nachhaltiges Wirtschaften – Integrierte Konzepte, Nomos Verlagsgesellschaft, Baden Baden.

[16] Bauer-Wolf, S., Payer, H., Scheer, G. (Eds.) Erfolgreich durch Netzwerkkompetenz – Handbuch für Regionalentwicklung. Springer-Verlag, Berlin, 2008.

[17] Westkämper, E., 2006, Einführung in die Organisation der Produktion. Springer-Verlag, Berlin.

[18] Thurm, R., Taking the GRI to scale. In Schaltegger, S., Bernett, M., Burrit, R. (Eds), Sustainability Accounting and Reporting, Springer Verlag Berlin, 2006.

[19] Kohl, H., Riebartsch, O., Sustainability Benchmarking. In: 9th Global Conference on Sustainable Manufacturing, GCSM 2011. CD-ROM.

[20] Mertins, K. ; Kohl, H.: Benchmarking – Leitfaden für den Vergleich mit den Besten, Symposion Publishing Verlag, Düsseldorf, 2009.

[21] Mertins, K., Kohl, H., Riebartsch, O., 2012, Sustainable Key-Figure Benchmarking for Small and Medium Sized Enterprises. In: Seliger, G. (Ed.), Sustainable Manufacturing, pp 309-313, Springer Verlag.

[22] Orth, R., Kohl, H. 2013, Towards Corporate Sustainability – a Small and Medium-sized Enterprise Perspective. In: Gracia, L, Barrutia, J. (Ed.), Proceedings 5th European Conference on Intellectual Capital, Bilbao, Spain, 2013, pp 323-334.

[23] Kohl, H., Hashemi, H. Al, Science Parks as the main Driver for the Development of National Innovation Systems in Resources-driven Economies! The Impoprtance of Intellectual Capital Management for Sustainable Manufacturing, In: Seliger, G. et.al. (Eds.), Advances in Sustainable Manufacturing: Proceedings of the 9th Global Conference of Sustainable Manufacturing. Springer Verlag, Berlin, 2011.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

1.2 Case study of ILVA, Italy: The impact of failing to consider sustainability as a driver of business model evolution

F. Tonelli [1], S.W. Short [2], P. Taticchi [3]

[1] Department of Mechanical Engineering, Energetics, Management and Transportation, Polytechnic School, University of Genova, Italy

[2]Institute for Manufacturing, Department of Engineering, University of Cambridge, United Kingdom

[3] Royal Docks Business School, University of East London, United Kingdom

Abstract

The case of ILVA steel works in Taranto, Italy demonstrates the potential impacts associated with failing toadequately consider environmental and social sustainability issues within the business model of the firm. This paper provides a review of the situation at ILVA today; the decisions and actions that contributed to the current situation since privatisation of the firm in 1995; and the choices now facing government, the local community, and the firm's owners going forward including a review of Best Available Techniques (BATs). The review is supported with relevant sustainability literature and explores how a more comprehensive assessment of sustainability considerations might be better integrated into business model evolution. The paper demonstrates that an inappropriate technology investment strategy that fails to consider broader concepts of value for the society and environment does not pay in the long-term, and that expectations of government support to mitigate negative impacts of business are becoming increasingly untenable.

Keywords:

Best Available Techniques; Business Model Innovation; Steel industry;Sustainable Manufacturing

1 INTRODUCTION

ILVA Taranto, Italy's leading steel producer made headline news across the world after being sequestered on the 26th of July 2012 by Taranto's regional PHJ(Preliminary Hearing Judge). ILVA was accused of creating an unprecedented environmental disaster; due to this, the PHJwanted ILVA to shut down theirblast furnaces and to encloseuncovered mineral stockpiles. The Judicial review court stated on the 6th of August 2012 thatthe ILVA disaster over the years isattributed to constant and repeated polluting activity perpetrated wilfullyby the owners and managers. In particular, the ILVA operating practices were such that they produced a malicious disaster through actions and omissions with a high potential for destructive outcomes for the environment (and society).The protracted action to force changes at ILVA Taranto was notable not just for the environmental violations and related health issues, but also for the strong counter-arguments presented by the labour trade union and the local community for continuing production in order to protect their employment, and the political activities to find a financing solution for the necessary improvements. The complexity of the situation, the economical, environmental and social trade-offs under discussion and the large set of stakeholders involved make the ILVA case a particularly interesting scenario for the discussion of sustainable business models[1].

This paper reviews the current situation at ILVA in terms of economic, social and environmental impacts, and explores the options available to ILVA and the Italian Government for improving/restoring the situation. The aim of this paper is to suggest that a more comprehensive assessment of sustainability considerations might be better integrated into business model evolution in order to avoid complex situations like the one reported.

The considered industrial case (steel) is of particularinterestwith respect to the concept of industrial sustainability [2]. All three TripleBottom Line (TBL)sustainability dimensions (environmental, social, and economic)are included,with apparent strong conflict between each dimension. Technology (afourthdimension from an industrialperspective) is also included as in this case it is crucial to determine and influence the first three dimensions.

Asustainability value mapping tool[3]can be used to assess the various forms of value and conflicting demands of the key stakeholder groupsas illustrated in Table 1.

The sustainability problem can be categorised as:

- **Environmental:**Assuming that the current level of pollution is the cause of health problems and disease in the region, is it possible to mitigate and fix this issue through selective and incremental interventions to improve the health and conditions of workers and surrounding populationwhile still preserving employment?
- **Social:**What is the social cost of a potential definitive closure or liquidation of ILVA Tarantoon the direct/indirect worker population (approximately 19,000 employees), and more broadlyon the related plants in other parts of Italy (Genova and Novi)? How can this be balanced with long-term health issues in the region?
- **Economic:**Can ILVA Taranto (Riva Group) afford the investments necessary to improve and upgrade the plant(s) in order to reach the required standards as suggested by BATs and related Reference Documents (BRefs) [4]? And if not, could the Government supply resources for these investments by applying several conditions and constraints to the ownership?
- **Technological:** are the BATs suggested in the AIA (integrated environmental authorisation) directive

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

[5]issued by the regional government really effective for the specific case and how is the best way to implement them?

Table 1: Value mapping analysis

Stakeholder group	Value currently captured	Value destroyed or missed	New Value opportunity
Value chain actors incl. investors, suppliers, etc. (Economicvalue)	Profit maximisation; Long-term relationships with suppliers;Localised operations	Reduced outputand potential stoppage; Reduced profitability/ market share	Investment in technology to conform to EU standards to boostproductivity and growth
Customers (Use value)	Price, product quality, supply lead-time	Reduced supplies and potential need to search for alternative steel producer	Switch to alternative non-Italian producer
Environment (Ecological Value)	Partial capture and containment of emissions and pollutants	Pollution; Loss of biodiversity; Reduced food production in region	Reduce emissions and pollution with technology; Contribute to clean up of contamination
Society (Societal Value)	Jobs (12,000 direct + 7,000 indirect in supply chain); Multiplier effect on regional economic activity and taxbase	Health risk and long-term care costs(respiratory disease, cancers); Job losses of forced layoffs;Agricultural contamination	Enhance living conditions for community; Safe jobs; Job creation; Reduce healthcare burden; Regenerate farming sector

2 BACKGROUND TO CASE

Italy is the second largest manufacturing nation in Europe with major strength in mechanics, machine tools, steel, chemical-pharmaceutical and rubber-plastics industries, foods and textile and clothing industry. However, the country is now in its longest recession in 20 years, and has languished in more than a decade of almost non-existent growth. Unemployment is at more than 11%; for under-25s it is more than 36%. Italy also has the second highest ratio of sovereign debt to GDP in the EU imposing severe austerity measures on the nation. Reinvigoration of the industrial sector to stimulate economic growth and employment is a major focus of policy makers.

Concerning environmental sustainability Italy is subject to EU regulations on emissions and pollutions. However, the judiciary system is slow-moving and sometimes alarmingly politicisedhence implementation and enforcement of environmental legislation has often been weak or none-existent. This is compounded by frequent changes in the political system that undermines continuity, and a significant level of crime and corruption within the country.

Within this context, the subject of this case study is the ILVA steel production plant in Taranto in the region of Puglia, Southern Italy (biggest steel production plant in Europe). ILVA is a joint stock company owned by the Riva Group, which is mainly based on the production and processing of steel. ILVA was previously the State-owned company IRI acquired bythe Riva family in the early 1990's. The group now consists of 42 plants operating in 8 countries across the world. Based on 2011 data the Riva group is the outright leader in Italy, the 3rd largest steel producer in Europe, and the 21st in the world by production volume.

The steel production process of a plant such as ILVA Taranto, and the process inputs and outputs including emissions and potential pollutants at each stageare illustrated in Figure 1.

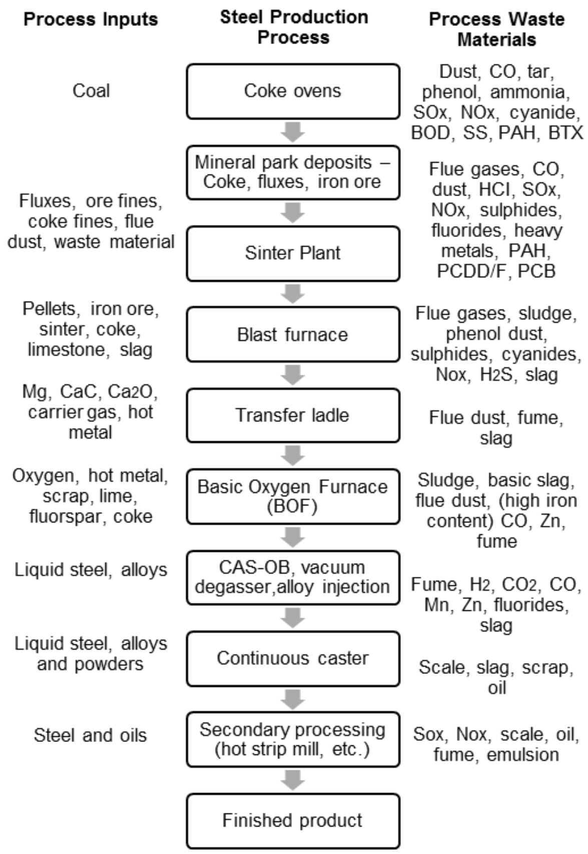


Figure 1: Typical steel production process
(Source: adapted from [4])

The operating equipment and facilities at ILVA Taranto integrated steel works consist of:

Hot area

- 10 Coke oven batteries
- 2 Agglomeration plants
- 5 Blast furnaces
- 2 LD steel works (each equipped with 3 converters of 330t. and 350t. respectively)
- 5 Continuous Casting machines (2 strands) for slabs

Rolling mill

- 2 Hot rolling mills for coils
- 1 Hydrochloric pickling line
- 1 Coupled pickling tandem rolling line
- 1 Electro galvanizing line
- 1 Hot-dip galvanizing line
- 1 Batch annealing line with 54 furnaces and 125 bases
- 2 Tandem skin pass mills Finishing and cutting lines
- 1 Heavy plates (2 stands) quarto reversing mill

Pipe mill

- 1 Longitudinally ERW pipes plant
- 2 Longitudinally SAW pipes plant
- 6 Pipe external coating and internal lining plants
- 1 External coating weighing down with concrete line

From the environmental point of view, the main polluting elements are PM10 (Particulate Matter smaller than 10 micrometres that are capable of penetrating deep into the respiratory tract and causing significant health damage), polycyclic aromatic hydrocarbons (PAHs) in particular the benzo(a)pyrene,dioxinsand heavy metals that can be carcinogenic. Stages of the production process that are considered particularly polluting are the mineral parks (storage areas for minerals used in steel production), the coke ovens,blast furnaces, and the agglomeration (sintering) plant.

3 CURRENT SITUATION AT ILVA

3.1 Economic situation

In 2011, Riva Group produced 16 Mt of raw steel, of which, 7.6 Mt of black coils, 4.1 Mt of wire rod, 2.0 Mt of concrete reinforcing steel (rebar), 1.0 Mt of rolled bars and billets, and 0.8 Mt of quarto plates. This equated to a turnover of about 10B€, with a reported net profit of 327.3 M€. This represented a return to profitability after poor performance in 2009 with turnover of 5.822B€(with a reported loss of 547.7 M€), and 2010 with 7.788B€(and a loss of 66.3 M€)[6]. The ILVA Taranto plant produces 8 Mt of steel annually, and distributes value of 865 M€ into the Taranto region; this represented about 75% of Taranto's GDP based on the Bank of Italy reports in 2008.

In the last 15 years the Riva Group has reportedly invested about 4.4B€ in the steel making plant. ILVA report that 25% of thishas been for environmental and safety enhancement, although it is not possible to clearly delineate between these investments and other forms of plant investment. About half of the investment on environmental and safety enhancements(447.3 M€) were reportedly for improvements to the coke oven, but it seems littlewas invested in the mineral parks coverage or more effective dust reduction measures; only recentlyhas ILVA begun to invest in the coverage of the conveyors.ILVA claim that higher rates of investment on environmental performance were not financially feasible. However, despite the reported losses at ILVA Taranto, the Riva Group had positive profits as discussed above, and the net asset equity of Riva Group is on an upward trend (currently around 4 B€), so financing of plant improvements appears possible, albeit perhaps not desirable to the owners and investors.

In July 2012, the Taranto judiciary ordered the shutdown of the plant's smelters in an attempt to force the Riva group to initiate the necessary investments. Facing inaction from ILVA, in November 2012 the Taranto judiciary took the extreme action of seizing 800 M€ of finished product in an attempt to force change. This action was overturned by a government decree to allow the plant to continue operating to protect jobs, but the dispute is still on-going.

3.2 Environmental issues

In 2010, ILVA emitted over 4,000t of dust, 11,000t of nitrogen dioxide, 11,300t of sulphur dioxide, 7.0t of hydrochloric acid, 1.3t of benzene, 150kg of Polycyclic Aromatic Hydrocarbons (PAH), 52.5g of benzo(a)pyrene, 14.9gof organic compounds, polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) and dioxin PCBdl. Levels of PCDD/F and PCBdl may be traced to specific sintering activities (agglomeration area) carried out within the plant.

To reduce emissions it is necessary to take measures forcontainment giving priority to the reduction of emissions of hazardous substances and metals. At present, ILVAhas largedeposits of coal,coke and other mineralsadjacent to the production plantin 30m high stockpiles. These are exposed tothe weather andparticularly duringdry south-easterly wind conditions dispersefine dust particles across the city creating values of PM10 beyond acceptable levels. The only method currently used for retaining this dust is to humidify the deposits using trucks that spray water over the stockpiles. Even though ILVA's certifications say they respected national laws and regional values (as measured in 2010), experts have pointed out that to achieve the emissions targets introduced in 1999 the humidification system would have requiredcontinuous automatic control to activate when conditions demanded. There was no such control, and without this the emissions cannot be considered compliant.

Emissions from other parts of the production process are similarly problematic. In accordance with European Community rules on the environmental performance ofsteel plant experts have found that: **"**in most of the production areas and/or process steps, the amount of the pollutants emitted are considerably higher than those that would be emitted in the case of adoption by ILVA of BATs with the performance as determined by BRefs". Furthermore, experts have concluded that if BATs were adopted for all phases of production, and not only discrete parts of the process, this would be more efficient in reducing pollutants and thus reduce emission loads from the entire plant. The difference found between the measured values and those expected from the application of BAT and those reported in BRef, shows that there is still a gap between the techniques used in ILVA and their effectiveness.

3.3 Social issues

Evidencesuggests that the environmental contamination has in turn created serious health problemsfor the employees and the wider Taranto community over the past decade[7]. The current enquiry into the site was launched after a 30% overall spike in local cancer rates was reported, with liver cancer up by 75% and upper uterine cancer up by 80%. Analysis of specific disease data provided by the Ministry of Health shows that while the cancer ratesfor the average Italian population are decreasing and the same phenomenon can be observed in the Puglia region, in Taranto cancer related deaths have been increasing.For example, in the period 2001-2008 lung cancer deaths in Taranto have increased by 5%, while the Italian average has decreased by

10%[8].Incidences of respiratory problems such as asthma are also reportedly higher in the area, with 90% of all babies affected.

Pollution also impactson quality of life in the Taranto community in other ways through contamination of land and water sourcesand the consequent risk of affecting the food chain. Residents are advised not to grow crops or raise livestock in the area (In 2008 roughly 2,000 sheep were slaughtered after their milk and meat were found to contain dangerous levels of dioxins). Furthermore,the city mayor has issued an instruction that children should not play in unpaved lotsto avoid contact with the omnipresent red and black dust particles that regularly blanket the city.

Countering the health concerns are the social benefits of long-term employment. ILVA Taranto employs more than 12,000 direct workers and 7,000 indirect workers, and is responsible for 75% of the 50Btof traffic handled by the Taranto port. Moreover the plant feeds ILVA'sGenova plant (1,760 workers), Novi plant (just under 1,000 workers), Racconigi's plant (200 workers) and other small plants. Due to the consequences of legal actions on the 26th of November 2012, the cold area production of the plant was stopped with an immediate potential layoff for 5,000 employees. Furthermore, the Puglia regionthat includes Taranto already suffers from unemployment levels of 25%, andILVA is relied upon as one of the main opportunities for stable employment.

So Taranto is facing a complex double problem –the population is worried about serious disease and other health issues caused by pollution, while at the same time employees and their dependents, and local suppliers and businesses are afraid to lose their jobs. Large strikes were organised in the latter half of 2012 in Taranto and in other cities where ILVA undertakes secondary processing, and the position of the workers (supported by the Unions) is to defend their jobs.

4 BEST AVAILABLE TECHNIQUES (BATS)

The technological performance of the ILVA's plant process has been analysed in the light of known BATs&BRefs[4], in order to identify available technologies to tackle each aspect of the firm's production processes and emissions.Particular attention is paid to the following areas: mineral parks (Table 2), coke oven (Table 3), sintering (Table 4), and blast furnace (Table 5). For each area the tables providethe current situation and technology employed by ILVA along with suggested BATs.

Table 2: Mineral parks BATs analysis

ILVA	ILVA PLANNED INVESTMENTS	GOVERNMENT REQUEST
Humidification of the deposits through the use of water cannon trucks	Construction of 2.2 km, 21 m high, barrier in High Density Polyethylene (HDPE); 20% reduction of the average inventory; Increase humidification of road and materials with fog cannons; Implementation of a monitoring system for humidification.	To cover all the mineral parks (Potential solution as used only by Hyundai in South Korea)

Table 3: Coke oven BATs analysis

PROCESS PHASE	ILVA (in progress)	BAT EU
Coal preparation	Secondary de-dusting	Techniques for minimising emissions
Oven charging	"Smokeless" charging machine	Preventingoven charging emissions
Coking	Coke ovens refractory partial revamping	Stabilise operation; Coke ovens maintenance; Sealing of emissions points; NO_x reduction; Pressure regulation of ovens; Improvement and cleaning of oven doors
Pushing of the coke	Fume capturing at coke discharging	Techniques for minimising emissions
Coke quenching	Conventional wet quenching	Improvement of coke wet quenching; Coke dry quenching
Treatment of coke oven gas	Desulphurisation	Reducing the number of flanges; Usinggas-tight pumps; Avoiding emissions from pressure valves; Desulphurisation
Coke handling	Secondary de-dusting	Using enclosures; Efficient extraction and de-dusting

Table 4: Sintering BATs analysis

PROCESS PHASE	ILVA (in progress)	BAT EU
Raw materials preparation	Secondary de-dusting; Control of oil in sinter feed	Abatement of dust emissions; Control of residues characteristics used in sinter feed; Reduction of VOC emissions
Sintering	MEEP (Moving Electrode Electrostatic Precipitator); Active carbon & urea injection; NO_x and SO_2 monitoring	Process optimisation; Advanced electrostatic precipitator; Bag filter with injection of active carbon and other additives; Reduction of NO_x and SO_2
Cooling and processing sinter	Secondary de-dusting	Abatement of dust emissions from secondary sources

Table 5: Blast furnace BATs analysis

PROCESS PHASE	ILVA (in progress)	BAT EU
Loading material	Stock-house de-dusting	Minimising stock-house emissions
Reduction and smelting	Venturi scrubbers blast furnace gas	Techniques for reducing dust emissions of blast furnace gas
Casting iron and slag	Cast-house de-dusting; Tar-free runner linings	Minimising cast-house emissions; Fume suppression during hot metal charging (with N_2); Using tar-free runner linings
Slag treatment	Condensation of fume from slag processing (partial)	Condensation of fume from slag processing

5 DISCUSSION

While finalizing this paper interventions will start in order to cover the mineral parks (36 months foreseen) as well as other plant improvements. Extraordinary government funded job protection measures will be activated for 6,417 workers of Taranto's plant until 2015. The job protection measures will mitigate the social impact to implement the Integrated Environmental Authorisation (AIA) even if they will be charged on collectivist base in an already challengingeconomic situation for Italy. Solidarity agreements could also be added in this case impacting on workers salary. Notwithstanding these measures, the situation within the Taranto plant is still critical and one head of department has recently been threatened with death.

The ILVA activity is under examination by technicians sent by the Minister in the area of environmental protection and concerning the law 231 of 2012 (see www.ispraambiente.it). The goal is to enableopen consultation of given prescriptionsto verify the implementation of the AIA plan. To this concern, the last report (28th of February 2013) proposed about 12 months of work to coverthe mineral parks according to technologiesidentified in the BATs analysis – new fog cannons and a monitoring system will include safety flares and six new sensors along the external perimeter of the plant. Within June 2013, 25 new measurement systems for emissions will be installed monitoring the following areas: agglomerate (sintering), coke oven, blast furnace and steelmaking milling. Concerning the continuous sampling of dioxin a system has already been installed andmonitoring protocolare being defined by the environmental agencies.

The coke areas (860 M€ of interventions of the nearly 2B€ estimated), will be improved starting from coke oven batterynumber 9,and completed within the second half of 2013, while batteries 3, 4, 5 and 6, have already been shut down and will be rebuilt together with battery 11. For the agglomerate, purchase orders have been placed for textile filters (see the BATs). Also, the blast furnace area will be improved within 18-24 months. In steel makingfacility 1 the roof floor will be closed and connected to fumes and dust aspiration systems, works have already been undertaken for 2 of 3 converters, and completion is expected for June 2013. Further, ILVA has launched the purchase order for a new textile filter (3.2 million cubic meters per hour). Finally, the raw material conveyor belts will be covered (385 belts for 200 km), 90%of which will be covered within 2014.

But what is the cost of so many interventions as requested by the AIA plan released the 26th of October 2012? The initial estimation was around 3B€to 4B€. This is a significant amount but still far from the original estimation made in the September judicial review that put the cost close to 10 B€for upgrade of the hot plant area. Surprisingly, the most recent estimateundertaken (Siderweb Study Centre) suggests of cost of approximately 1.5 B€. If confirmed it will remove any doubt about the economic feasibility of the plan and so remove the threat of such investments undermining the future survival of the enterprise. However, immediately after this statement, ILVA presented a plan costing 2.25 B€.

Thus the lesson learned is that combining environmental, social, economic, and technical problems together results in the most disparate estimations and that the estimation process is strongly opaque, especially in this specific case. But this apparent unclearness has, in our opinion, other possible reasons. The AIA released by the Minister defines and prescribes the company to reduce pollution by applying the BATs. However, the company, by law, takes the final decision on what to apply in the light of economic feasibility. Particularly, the assessment included in the AIA (article 8, law decree 59/2005), considers the best technologies in an absolute way and not with respect to a cost-benefit criteria. The cost reduction proposed by ILVA, against the first ministerial estimation, is justified by the fact in September the estimation process was done only in an approximate way. Now feasibility and design quantification are in the operative phase and only 20% variability is acceptable before closing all the contracts for consequent activities.

Another important issue concerns the reliability and reality of the interventions undertaken previously. On 23rd January 2013 ILVA stated that 65% of AIA prescriptions were already in place; that is in contrast with the level of remaining intervention costs and the related uncertainty arising. A further unclear aspect relates to the individual investment for each plant and sub-plant. For instance, for the coke areas, 860 M€ is the cost estimated to refurbish and rebuild, even though in a document dated 2012 entitled "Investments for Environment"[9], the Company stated to have already invested since 1995 up to 2011, 480 M€. Surprisingly, after an investment of 30 M€ per year in a single area, the area now apparently needs to be completely rebuilt.Other estimations are opaque and difficult to practically correlate to effective investments in industrial sustainability; the most probable value could be around 689 M€ in a period spanning from 1995 to 2006.

Considering the investments from the Government and tax payers'perspective, it appears that assuring job protection of more than 5,000 workers up to 2015 will result in a collective cost of more than 800 M€ to the public purse. Surely it would be better to oblige privately owned companies to respect regulations adopting the required investments (even if this means partially supporting them from public sources) before reaching this critical disequilibrium point, instead of imposing almost entirely, the huge social, economic, and environmental (and hence serious health issues) on the country and citizens, and finally claiming for the evident "unsustainability" of these industrial practices/facilities.

6 CONCLUSION

The hard choice to risk dying of cancer rather than face the ignominy and hardship of unemployment for workers, the institutional obligations to prohibit environmental pollutionto guarantee health and wellbeing for the citizens of the territory, and the conflictingmyopic profit-oriented management strategy of Riva Group, pose an unquestionable industrial sustainability challenge. The Riva group has claimed that compliance costs were prohibitive. However, looking at the economic and financial performance of Riva Group, it is hard to acceptthey couldn't support the right investments to renovate the plant since 1995, and yet harder to believe they are now demanding the government to pay.

Some commentators have suggested that inappropriate ownership of the company, prolonged State inaction, and corruption are the cause of the problems. There is almost certainly some truth in this as evidenced by the fact that polluting activities have continuedsince the 1990's despite environmental concerns raised by government, and award of full environmental certifications ISO14001 and ISO18001 right up to the current date. However, ultimately it appears that the Riva family and the management of ILVA have simply followed a contemporary shareholder-centric approach to business of profit maximisation, with an expectation that government will continue to support by taking responsibility forthe external social and environmental costs[10].

The ILVA Taranto case isan extreme example of environmental pollution and social harm due the size of the plant, its national and regional importance, and the duration of the problems, but the problematic business approach underlying the issues is not uncommon. Recent, highly public examples demonstrate similar compromises in pursuit of profitsacross a broad range of sectors. For example, British Petroleum's environmental disaster in the Gulf of Mexico in 2010; suicides and labour disputes over pay and working conditions at iphone supplier Foxconn in China 2010-2012, and the collapse of an apparel factory building in Bangladesh in 2013 killing many hundreds of workers.Similar scenarios are likely to occur repeatedlyparticularly in regions where regulations and governance to protect the environment and society are weakuntil business models focused on short-term profit maximisation are addressed. This is perhaps particularly pertinent to large nationally strategic industry sectors.

In the past these enterprises may have benefited from implicit guarantees of the State, enabling them to maximise short-term profits for management and owners while acting in areckless manner towards their broader stakeholders including the environment, workers and society. The judicial challenge in this particular case of ILVA demonstrates that the changing dynamics of a recessionary and debt-laden Europe makes such an expectation of government and taxpayer largesse look increasingly unsustainable.Furthermore, pressure on firms to adopt a more holistic approach to business sustainability seems likely to increase under changing public awareness and attitudes towards the role of corporations in the wake of the recent examples of corporate neglect of suppliers and the environment in pursuit of profits.

Applying a scientific and rigorous industrial sustainability approach will be the only way to resolve paradoxes like the one presented in this case; production (even of steel) is possible in a way that guarantees workers and community health and wellbeing. Technology can provide effective solutions as defined in BRefs and demonstrated by leading producers in Germany, South Korea and Japan who have pioneered and championed best available techniques for the sector. Such firms, far from being weakened by the investment costs are now enjoying strong competitive advantages in a global market place, supporting, rather than damaging their local environment and communities. Such innovation is more than just technological though – it requires a fundamental shift in perception of the value proposition of the firm to embrace the needs of broader stakeholder groups, reducethe dependency on government support and fully reconsider how the firm does business, whichare at the core of the firm's business model.

In conclusion, appropriate consideration of social and environmental sustainability within the business model as suggested by Stubbs and Cocklin[1]will therefore increasingly become core to ensuring economic sustainability and hence long-term survivability of the firm and protection of national strategic capabilities and jobs. Firms and government policy will need to shift to a more holistic perspective of value creation, based on the TBL and BATs.

7 REFERENCES

[1] Stubbs, W., Cocklin, C., 2008, Conceptualizing a "Sustainability Business Model", Organization & Environment, 21:103–127.

[2] Tonelli, F., Evans, S., Taticchi, P., 2013, Industrial sustainability : challenges , perspectives , actions, International Journal of Business Innovation and Research, 7(2):143-163.

[3] Short, S.W., Rana, P., Bocken, N.M.P., Evans, S., 2012, Embedding Sustainability in Business Modelling Through Multi-stakeholder Value Innovation, Proceedings of the APMS 2012 Conference, Advances in Production Management Systems, Rhodes, 24-26 Sept 2012.

[4] Remus, R., Aguado-Monsonet, M., Roudier, S., Sancho, L.D., 2013, Best Available Techniques (BAT) Reference Document for Iron and Steel Production , www.bvt.umweltbundesamt.de/.

[5] AIA, 2013, AIA Ministero Dell'Ambiente - L'autorizzazione integrata ambientale - Introduzione, http://aia.minambiente.it/. Accessed Feb 2013.

[6] Riva, 2013, Profilo Riva Forni Elettrici, www.rivafornielettrici.com/it/fornielettriciprofilo.aspx. Accessed Apr 2013.

[7] Kington, T., 2012, Italian steelworks accused over cancers wins reprieve, In: Guardian.co.uk. www.guardian.co.uk/world/2012/nov/30/italy-ilva-steel-factory-cancer. Accessed Apr 2013.

[8] Comba, P., Conti, S., Iavarone, I., et al., 2012, Ambiente e salute a Taranto : evidenze disponibili e indicazioni di sanità pubblica, www.salute.gov.it/imgs/C_17_pubblicazioni_1833_allegato.pdf. Accessed Oct 2012.

[9] ILVA, 2013, Policies for Environmental Protection - ILVA Taranto, www.ilvataranto.com/ambiente.aspx. Accessed Apr 2013.

[10] Porritt, J., 2005, Capitalism : as if the world matters / Jonathon Porritt. Earthscan, London.

1.3 Interdisciplinary planning of sustainable value creation modules with low income communities in developing countries

J. Palacios [1], M. Pinto[2], Y.M.B. Saavedra[3], B. Müller[1], T. Guidat[1],

[1] Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany

[2] Laboratório de Tecnologias de Apoio à Redes de Colaboração, Universidade Federal do Espírito Santo, Brazil

[3] Environmental Engineering Sciences; Department of Production Engineering, São Carlos Engineering School, University of São Paulo, Brazil

Abstract

Value creation activities are normally considered to take place in relatively well developed areas of most countries. This is especially true when referring to developing countries where income generation possibilities are normally reserved to urban centers with adequate infrastructure, access to supply chain networks and trained human resources. In order to level quality of life and social conditions of low income rural and urban communities to the regional prosperous areas, opportunities to create local economic development have to be generated. A way to contribute towards the achievement of this end is the generation of sustainable local value creation modules. To achieve this, the integration of several knowledge areas is most of the times necessary in order to secure a smooth implementation in the field increasing thus its success chances. This contribution proposes a method to construct interdisciplinary teams capable of define, develop and conduct projects intending the implementation of value creation modules in economically disadvantaged communities in developing countries.

Keywords:
Value creation modules, interdisciplinary teams, developing countries, capacity building

1 INTRODUCTION

Global community is nowadays a reality. Accordingly to Gurría (2013), developed and developing nations, North and South hemispheres became so interdependent that sustainable development goals, poverty and human development agenda are ubiquitous [1].

Since sustainable development entered the global agenda in the nineties, important results were achieved. Poverty has declined and in 2013 there are 620 million fewer extremely poor people in the world today than in 1990 [1]. Brazil, Bangladesh and Mexico pioneered innovative approaches to target poor households, like the Brazilian Program *Minha Casa, Minha Vida*, which has benefited more than 3.2 million people between 2009 and 2011 [2]. Improvements in health conditions, social protection, food security and school enrolment are also reported (World Development Indicators, 2013) [3]. However, great efforts against poverty are still necessary. According to World Bank estimates globally there are about 4.2 billion people living on less than 5 dollars a day, while the situation is even worse in some parts of the globe. In Sub-Saharan Africa for instance, almost half of the population still lives on less than $1.25 a day. The situation is also reflected by some other figures: close to 2.4 billion people around the world lack proper sanitation facilities and 1.1 billion people lack a safe source of drinking water. Low income and its associated substandard life conditions are related to lack of good quality jobs or rent generation opportunities. For example, in Africa, the unemployment rate reaches 40% in Kenia and 48% in Senegal Poor distribution of wealth makes the poverty situation even worse in some nations. Data from OECD (2011) show that in Chile, the richest 10% of the population have incomes 27 times those of the poorest 10%; while in Brazil this ratio stands at 50 to 1 [4]. Finally, the efforts against poverty are hampered by climate change. According to the United Nations Human Development Report (2013), the number of people living in extreme poverty could increase by up to 3 billion by 2050 unless urgent action is taken to tackle environmental challenges [5].

Therefore, it can be considered that poverty reduction is still an enormous challenge for all the humanity and that we need innovative approaches to face it.

2 VALUE CREATION MODULES

2.1 Motivation

In what is without a doubt a very simplistic economic categorization of the global community, countries are divided in two groups: developed or more developed countries (MDCs) and developing or less-developed countries (LDCs). There are still no absolute criteria to determine the belonging of a country to one group or the other, but it is generally accepted that the first group is composed by countries that present high Human Development Indexes (HDI) and possess a highly developed economy and technological infrastructure. The LDCs in turn, are countries which evidence lower levels in socioeconomic indicators such as the HDI and lack the technology levels of the MDCs. According to the International Statistical Institute (ISI), today there are 144 LDCs in the world, 18 are localized in Latin American and Caribbean and 54 are African states [6].

Regardless obvious differences still existing between the two economic blocks, especially concerning the quality of life and socioeconomic development possibilities, globalization has made possible in the last decades to reduce the breach. According to United Nations Development Program (UNDP), in the last decade, most LDCs accelerated their achievements in education, health and income generation possibilities. By 2020, the combined economic output of the

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

three leading developing countries, Brazil, China and India, is expected to surpass the growth of Canada, France, Germany, Italy, United Kingdom and United States [7].

This prosperity however, is benefiting only a limited percentage of the population in the LDCs. In the case of Latin American and Caribbean and according to the Inter-American Development Bank (IDB) every third family lives in a structurally unstable building, constructed with low quality materials and lacking basic services [8].

When it comes to income generation possibilities, the international labor organization reports that the informal sector has gained increasing acceptance in Latin America. Some 30 million persons now work outside the modern economy in low-productivity jobs with marginal incomes; many of them living in poverty [9]. This situation is especially worrisome in rural and marginated urban settlements where the lack of development opportunities, edge the community members to migrate to densely populated but wealthier urban areas.

The concept of sustainable manufacturing refers to the concept of local Value Creation Modules (VCMs) and the generation of regional VCM networks as a mean to decentralize economic development and trigger communities' wellbeing through the rational exploitation of local material and human resources.

According to Seliger, every VCM consists of five main factors, namely: product, process, organization, equipment and human. In modern sustainable societies, each one of these factors are to be oriented towards the generation of value, where value should be understood not only as economical but also environmental and social [10].

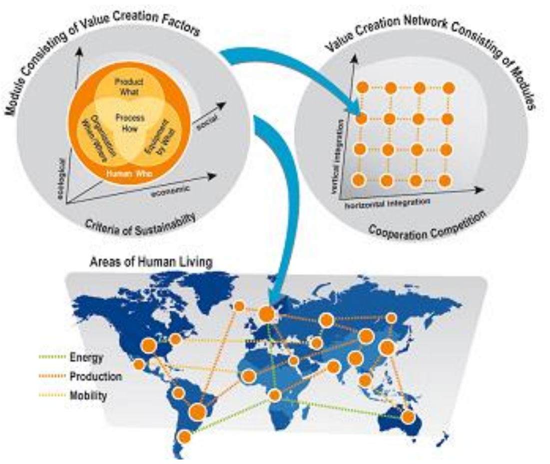


Fig. 1 Factors present in value creation modules and networks [10]

Considering the context of a low income community in a developing country, a VCM can be structured as a set of low to mid-tech value adding processes, usually limited to a few tens of square meters of confined space and producing finished or semi-finished products for the local or regional consumption. These modules have the potential to be part of elaborated value creation networks or act as independent decentralized productive units with local suppliers and customers.

Similar to many activities undergone by modern societies, the planning, development and operation of a VCM requires in most cases, participation of groups of people, commonly known as teams, with a full set of complementary skills to complete a series of specific tasks throughout each one of the project's planning and realization phases. Depending of the complexity and variables of the project, including size, environment, end product or service and infrastructure, involvement of interdisciplinary teams becomes a determinant key to achieve not only implementation success during the development phases but also economic success during its operative life.

These interdisciplinary teams are defined as a coordinated group of experts from different fields who work together towards a unique common goal. Team members operate with a high degree of interdependence, share authority and responsibility for self-management, are accountable for the collective performance, and work toward a common goal and shared rewards [11].

In this sense, this contribution has the goal to present an interdisciplinary initiative to design Sustainable Value Creation Modules for low income communities in developing countries.

The method utilized is the result of several multidisciplinary projects and project oriented teaching activities conducted by the department of machine tools and factory management of the Technical University Berlin (TUB) in collaboration with internationally renowned universities in Africa and Latin America such as the Stellenbosch University, South Africa (SU), the Universidade do São Paulo, Brazil (USP), the Universidade Federal do Espírito Santo, Brazil (UFES) and the Pontifícia Universidad Católica de Chile, Chile (PUC).

This contribution will focus therefore on the activities concerning the planning and realization phases of the VCM as an autonomous entity in a low income area. These activities include, but are not limited to; project scope, project management, value creation processes' design, factory planning and layout, capacity planning, machine tool selection, supply chain design, community integration and sustainability assessment.

2.2 Value Creation Factors

As mentioned previously, every VCM is assumed to consist of five basic factors which are shaped according to the user's requirements or "voice of the customer". These factors have special considerations when it comes to drive sustainable development of low income communities

2.2.1 Process and Equipment

Processes that have to be performed in VCMs can be regarded as manifold. Reichwald et al. states the following processes, VCMs generally have to cover in the operative level [12]:

- Admittance of customer preference or in case of low income communities, customer's necessities and raw materials available
- Translation of the customer preference into customer individual product characteristic,
- Individual production of the desired product,
- Distribution of the product. The community in this case support the VCM whilst the utilization phase and initialization of the rebuy.

In contrast to this, Zäh and Aull define the following main activities in dependence on Porter's value chain [13], [14]:

- Product definition,

- inbound logistics,
- internal logistics,
- manufacturing and assembly,
- external logistics

Machine tools on the other hand are normally tailor-made solutions, usually manufactured by local producers, members of the community or involved stakeholders

2.2.2 Product

Having a deeper look at the core activity of value creation, the manufacturing and assembly, a variety of examples are available that illustrates the production process within VCMs. Postawa et al. (2009) introduces a disassembly process for printed circuit boards (PCB) performed by a value creation network in Brazil. After the separation of electronic devices by help of adjusted manual aids at a manual workstation, reusable units are tested and sorted either into units being inserted into a solar oven or units sold to a refinery. Solder is then removed and components are separated from the resin-board. By help of a manual driven centrifuge, components of the PCB will be removed. The solder is collected extra while the remaining components are grouped by specific categories on different stocks to be sold to a refinery or industry. [15].

Postawa et al. (2011) proposes a VCM to produce cocoa paste. After the breaking of the harvested and dried cocoa beans, a sorting, roasting and grinding of these beans is performed to receive the final product of cocoa paste [16].

Hu and Seliger (2012) introduces in their contribution a further process related to Collaborative Research Centre 1026: "Teaching and training". Hereby the VCM is regarded as a "Learnstrument". [17]

2.2.3 Organization Human

The type of business model of a VCM determines not only the source of income but also determines profit utilization of the enterprise. Depending on the focus of profit utilization, a VCM can be categorized as follows: Profit-maximizing companies create shareholder value as an ultimate goal. Non-profit organizations create social value instead by consuming investment from donors. Social businesses create social value too, but aim at achieving at least self-sustainability as a result of their activity.

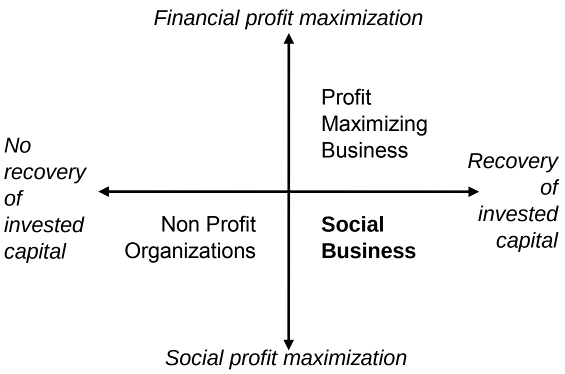


Figure 2: Classification of Social Business [18]

Main goal of traditional business models is to sustain an economic value. The other components of sustainability, namely the ecological and social development are not considered as essential by top managers in traditional for-profit companies [19]. As the necessary equilibrium between these dimensions is challenged in a large majority of ventures, there is a need to balance social, economic and environmental aspects by reforming the logic of individual profit maximization [20].

The design of value creation modules in a specific community of a designed country is closest to the definition of "social bricoleur" classification. The action is specifically tailored to address a well-defined and local issue. The aim is to enable local entrepreneurs to fulfill locally discovered needs of the community with locally available resources. The business model is not intended to be replicated at a large scale and the activities developed are a competitive alternative to the ones of existing private companies.

One possibility to model a business is to define the classic three components:

1. Value proposition of the product or service offered to the final consumers,

2. Value chain composition to ensure durability of the supply and distribution of the products through the sustainability of the local partners of the venture,

3. Revenue model, to indicate how the company will cover its fixed costs and to anticipate the development strategy.

A social business has a social objective. This requires introduction of a fourth component:

4. Social benefits tracking, to measure the effects of the social venture on the local stakeholders, such as employees, customers and suppliers.

3 INTERDISCIPLINARY PLANNING OF VCM

3.1 Academic background

In most MDCs and many LDCs, universities have acted in recent years as driving entities and spearhead of the implementation of sustainable manufacturing concepts in the national production areas, weather through the education of professionals and technicians who will act as practitioners of the methods in the future or, through direct intervention and collaboration with the communities, governmental bodies, industry or relevant stakeholders. In some cases, as the ones described next, a combination of both methods is also possible by means of the development of innovative project oriented teaching programs.

"Engineers without Borders–USA" (EWB), formed in Boulder, Colorado, developed a result-oriented strategic planning of help to poor communities around the world while developing internationally responsible engineering staff [21]. The staff is mixed between permanent board of directors and project managers, centralizing the information for partners universities located in the USA and referred to as "chapters". Each chapter acts as an independent structure and organizes its own resources.

"Engineers for a Sustainable World" (ESW) uses the same principle of a centralized organization working together with affiliate partners, run independently by local leaders. However, distinction is made between collegial and professional chapters to allow the inclusion of private organizations in the projects led in communities. The collegial partners are encouraged to include the project solving activities in the curricula of students or even develop courses on the application of sustainable engineering. Local organizations' leaders share monthly on their achievement and the national board initiates the information sharing activities [22]. Similar approach is retrieved in the Engineers in Technical, Humanitarian Opportunities of Service Learning *(*ETHOS) program focused on the capacity building in the poorest communities.

The Technische Universität Berlin (TUB) has also long experience in the development and management of project-based international student activities. Such programs started in 2002 in the field of production engineering, with the Global Product Development (GPD) course [23]. The GPD course was held until 2008 and gathered students from three universities: Seoul National University (Korea), University of Michigan in Ann Arbor (USA) and TUB (Germany). The primary objective of GPD was to effect systematic knowledge transfer of method and societal competencies by using extensive case studies. Internet lectures were delivered by the teaching staff of the cooperating universities and students recruited from the universities developed prototypes of globally marketable products. Two face-to-face meetings of participants held early and late in the term, supplemented the virtual meetings.

The GPD initiative served as a precursor for further projects, Global Engineering Teams (GET) is an international, multicultural team- based approach at solving practical engineering problems originating in companies. GET groups is led in virtual and international students' teams. The initiative fosters teamwork and digital collaboration among students with different technical and cultural backgrounds, and is providing a unique by opportunity for students to manage concrete industry challenges. GET has three main objectives:

1. Solving engineering tasks in international groups
2. Using interdisciplinary project-oriented and practical best practices
3. Considering engineering tasks holistically to promote global sustainability

The latest of collaborative international capacity building programs of the TUB, is the Housing – Manufacturing – Water project (HMW). HMW was born in 2009 as a collaboration initiative between the Technische Universität Berlin (TUB) and six partner universities in Africa, Latin America and India. Since its inception, HMW pursued the integration of multidisciplinary knowledge fields into yearly common learning projects and workshops where urban design planers as well as manufacturing and water engineers cooperate in proposing adequate strategies for the achievement of UN's Millennium Development Goals, especially those referring to the development of sustainable housing areas, supply of drinking water and generation of income sources. The HMW Project has simultaneously the objective to build capacity in the implementation areas together with its local partners; this is achieved through seminars and lectures for the next generation of professionals and the training of community members.

The HMW project has lately served as platform to develop further the planning methodology to develop VCM through interdisciplinary teams presented in this contribution.

3.2 Proposed Method

The starting point to define a project on VCM for low income communities is to change the preposition "for" to the preposition "with". This change impacts the whole process because the researchers accept they don't have enough knowledge about the low income communities' reality necessary to perceive the value creation possibilities that exist in their environment.

The interaction must be personal and close which means: Identify local people who are interested in promoting local development and became themselves stakeholders. They can be local community leaders or social entrepreneurs that act individually or through NGOs, for example, in the community.

The core team of researchers and implementers conduct following initial activities:

1) Conduct visits to the community sites, interviews and group activities with community stakeholders based on predetermined templates as the Business Model Canvas. Objective is to determine what kind of "value delivery" the community perceive and to whom they think it is possible to delivery such "value", meaning, the customer identification.
2) Roughly define the concept of "business" that can be developed with such preliminary information.
3) Bring together the community stakeholders with representatives of the possible "clients" and other intermediate agents in the business production chain. They become market stakeholders (or enterprises stakeholders). Experts in the specific field are also invited. Altogether, they discuss the value creation proposition and refine the concept of the "business" that the VCM must accomplish.
4) At this point, the academic team formulates a proposition of VCM (a power point slide may be enough). This proposition is then presented to all the stakeholders and, if approved, it is turned into a VCM project. The main requirements of the VCM in terms of end product to be produced, overall production goals, and implementation site are defined by all the involved parties who sign documents that will guide the project development phase.
5) The interaction with all the stakeholders is kept alive during the development phase through regular meetings to evaluate if the project is addressing the stakeholders expectations.

Once the VCM and its goals are defined, the integration of an interdisciplinary team commences by identifying concrete knowledge areas required to conduct and realize the tasks deemed as necessary for the realization of the objectives of the VCM. Experts of the identified knowledge fields, usually academics, industry representatives and NGO members, are then contacted and presented with the project, its overall scope, areas of direct impact, expected contribution and the involved stakeholders. Finally the interdisciplinary team is formed and subdivided in sub teams according to synergy demands and interdependency necessities.

A standard working group formed to plan VCMs would include at least following sub-teams: Project management, business model and community integration, product development and process design and machine tool design.

The project management group would be in charge of define the scope of the project, set up a timeline, define deliverables by interpreting the voice of the customer (stakeholders) and create the internal communication channels between the sub teams and between the sub teams and the stakeholders. The tasks of the project management team include as well the monitoring of the project throughout its realization and if necessary conduct modifications to the plan after consultation with the stakeholders.

The deliverables expected from the business team can be classified in three main categories. First an analysis of the current market environment is established as well as the potentials for a new entrant in this domain. Based on observations from the potential customers, this part ensures that the technical solution delivered will have excellent integration chances with regard of stakeholders' expectations. Secondly, several concepts suggestions will be deduced from the market analysis. The best concept will be selected for its influence on an agreed criteria list. It will allow the creation of specifications to be respected from the product and process development teams. A last deliverable category will aim at identifying major recommendations for the implementation phase of the selected concept, such as a detailed activities planning and financial projections. The principle of co-creation will be respected all along the project realization thanks to the contact with community leaders through the stakeholder network.

The process design team is expected to, primarily via systematic product design, define the physical output of the VCM, whether this would be a finished or semi-finished good. Common deliverables at this stage are market and raw material research, product's definition and prototypes and price definition. The second task of this team is the design of the value creation chains. To this stage, following deliverables are expected: site layout, value stream map, definition of necessary employee qualification, design of work places, legal framework, etc.

Finally, the machine tool design team will elaborate on the hardware requirements of the VCM in order to produce the goods defined by the process team. The team is responsible to report adequate production technologies to achieve the necessary value creation processes and determine suitability of the machine tools existing in the market. In case it is necessary, the team is also responsible to adapt existing technologies to the necessities of the VCM. This is to be done considering a closed loop lifecycle and the involvement of local producers.

A kickoff event, ideally at the implementation site within the community, serves usually as platform to set specific objectives per sub teams, a project timeframe, resource allocation per area, internal communication protocols and establishment of feedback channels with external stakeholders.

Experience has shown in our case that the biggest challenges are to be expected while interpreting the voice of the customer, means transforming the stakeholders' demands into specific work packages and/or deliverables, and also during the setup of communication and information's protocols between sub teams, where miscommunication or personal biases by individual team members slows or partially hinder delivery of integrated results. Resolution strategies like the one proposed by Behfar-Peterson [24] have been considered and utilized during our experience in the field but will not be discussed further in this contribution.

In the particular case of the projects realized by the TUB and its international partners, the expert teams are complemented with groups of graduate students of the relevant knowledge areas and members of the participant institutions, who participate directly in the planning phases of the project and conduct most of the operative and development tasks throughout the academic semester.

The involvement of graduate students pursues mainly two objectives; on the one hand, suitable solutions towards the achievement of the VCM's objective are provided by the student groups under close supervision of recognized experts, reducing thus development costs for the VCM without sacrificing quality in the results. On the other hand, the delegation of core responsibilities already during the planning and organization phases as well as direct participation during the execution and field work, provides the student with practical expertise through the conduction of project oriented activities complementing his/her theoretical knowledge in a way comparable to professional experiences.

The participation of international students as in the case of TUB's HMW and GET initiative, provides the project as well with a multicultural dimension which benefits not only the result of the implemented solution, through the integration of acclimatized methods and technologies and inclusion of objective perspectives, but also promotes the global dissemination of knowledge and acquired experience, achieving thus a multiplication effect.

Finally, once the final results per area are ready and integrated, a holistic proposal is presented to the local project stakeholders and community members. Since they have been continuously part of the project's development, few modifications can be expected. Further phases of the project, not part of the scope of this contribution, such as implementation and running, are then commenced.

4 CONCLUSIONS

Generation of decentralized VCMs as key driver to achieve sustainable development in low income communities of developing countries has been the motto of international development organizations and academics in the last decades. The department of machine tools and factory planning of the technical university Berlin, together with internationally renowned African and Latin American university partners, have developed vast knowledge in the integration of multidisciplinary teams in charge to set up income generation solutions in form of local value creation units in direct collaboration with the community and other relevant actors. The positive results of this symbiosis namely, improved success chances and community ownership of the project, have been confirmed by sociologist and technical experts alike. A methodology on how to integrate these interdisciplinary teams, based on the involvement of the community and the forming of student groups, has been presented in this contribution.

5 FURTHER DEVELOPMENTS

The above developed method has to be developed further based on new experiences gained through its application in new case studies. Current work of the department centers in developing integrated small scale factory planning methodologies in so called “mini factories” which takes into account particular socioeconomic conditions of disadvantaged areas in developing countries. Such a methodology has to be further developed in collaboration with social scientists who are able to understand the local requirements of the community in detail, business economists, that can adapt capable business models to the specific local conditions and engineers, who evaluate the technical feasibility under the regional requirements.

To distribute the idea of the generation of local income in poor communities, a platform has to be developed. An open knowledge solution containing detailed material on “how to build my own VCM” should be developed and put to the disposition of potential users in disadvantaged communities. By means of a bidirectional platform, the user would be able to troubleshoot original concepts and generate a continuous improvement loop with others users of the platform.

6 REFERENCES

[1] Gurría, A.: “Innovative Approaches to Poverty Reduction, Social Cohesion and Progress in a Post-2015 World.” OECD Secretary-General, Global Forum on Development, Paris 2013.

[2] CEF, 2011. Relatório da Administração CAIXA - 1º Semestre 2012. 28p. http://downloads.caixa.gov.br/_arquivos/caixa/caixa_demfinanc/RELAT%C3%93RIO_DA_ADMINISTRA%C3%87%C3%83O_1S12.PDF. Access: 24th, April, 2013

[3]. World Development Indicators (2013). http://databank.worldbank.org/data/views/variableselection/selectvariables.aspx?source=world-development-indicators. Access: 24th, April, 2013.

[4] OECD.: “Divided We Stand: Why Inequality Keeps Rising.” December 2011.

[5] United Nations Human Development Report (2013).: “The Rise of the South: Human Progress in a Diverse World. UN Development Programme. NY”. http://hdr.undp.org/hdr4press/press/index.html. Access: 24th, April, 2013.

[6] The International Statistical Institute (ISI).: “Developing countries.” http://www.isi-web.org/component/content/article/5-root/root/81-developing. Access 30.04.2013.

[7] United Nations Development Programme (UNDP).: “2013 Human Development Report.”: http://www.undp.org/content/undp/en/home/librarypage/hdr/human-development-report-2013/. Access 29.04.2013.

[8] Parente, S. “O Mercado Financeiro e a população de baixa renda. Comissão Econômica para a América Latina e o Caribe”.2003

[9] Tokman, V.: “Policies for a heterogeneous informal sector in Latin America. International Labor Organization.” 1990

[10] Seliger, G. ed.: “Sustainable Manufacturing – shaping global value creation”, Berlin 2011

[11] The business dictionary http://www.businessdictionary.com/definition/interdisciplinary-team.html. Access 22th, April 2013

[12] Reichwald, R.; Stotko, C.M.; Piller F.T.: „Dezentrale Minifabrik-Netzwerke als Form des Real-Rime Enterprise: Konzeption, Flexibilitätspotenziale und Fallstudien“ in Kuhlin, B.; Thielmann, H. (Hrsg.): „Real-Time Enterprise in der Praxis: Fakten und Ausblick. Springer Publishing“, Berlin Heidelberg, 2005.

[13] Zäh, M.F.; Aull, F.: „Minifabriken: Die Zukunft effizienter Produktion“ in „Marktnahe Produktion individualisierter Produkte: Industriekolloquium des Sonderforschungsbereichs 582“. Herbert Utz Verlag GmbH, München, 2004.

[14] Porter, M.E.: „Competitive Advantages: Creating and sustaining superior performance“. Free Press, New York, 1985

[15] Postawa, A.B.; Brandão, D.; Rubin, R.S.; Seliger G.: „Configuration of Value Creation Modules, instantiated in Mini Factories for Disassembly of Printed Circuit Boards“ in „Sustainable Product Development and Life Cycle Engineering: Proceedings of the 7th Global Conference on Sustainable Manufacturing”, Micro Print Ltd., Chennai, 2009.

[16] Postawa, A.B.; Siewert, M.; Seliger, G.: „Mini Factories for Cacao Paste Production“ in „Sustainable Manufacturing – Shaping Global Value Creation: 9th Global Conference on Sustainable Manufacturing”, Universitätsverlag der TU Berlin, 2011.

[17] Hu, J.; Seliger, G.: „Sustainable Product-Service Systems design towards resource efficiency“ in „Towards Implementing Sustainable Manufacturing: Proceedings of the 10th Global Conference on Sustainable Manufacturing”, Istanbul 2012.

[18] Yunus, M., Moingeon, B., Lehmann-Ortega, L.: “Building Social Business Models: lessons from the Grameen experience”, HEC Paris 2009 – working paper 913.

[19] Thompson, J., Alvy, G., Lees, A.: “Social entrepreneurship — a new look at the people and the potential”. Management Decision 2007 38, 328–338.

[20] Schumpeter, J.A.: “Capitalism, socialism, and democracy”. Harper and Brothers, New York. 1942.

[21] Amadei, B.: “Program in engineering for developing communities: viewing the developing world as the classroom of the 21st century”. Proceedings of Frontiers in Education conference. Piscataway, NJ: Institute of Electrical and Electronics Engineering, 2000.

[22] ESW – Engineers for a Sustainable World http://www.eswusa.org/mission-vision, Access 01.05.2013

[23] Eisenberg, M. and Scheffer, C.: “Blended learning in global engineering teams. ASEE global colloquium on engineering education”. Cape Town, South Africa 2008.

[24] Behfar, K; Peterson, R.: “The Critical Role of Conflict Resolution in Teams: A Close Look at the links Between Conflict Type, Conflict Management Strategies, and Team” Outcomes, Journal of applied psychology 2008.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

1.4 Strategic innovation priorities for sustainable manufacturing in Australia

K. S. King [1]

[1] Future Manufacturing Flagship, CSIRO, Melbourne, Australia

Abstract

This paper presents a strategic perspective and 3 sustainable manufacturing innovation priorities for the Australian manufacturing sector. They are, improving resource efficiency, developing new business models and adopting new technology. These are not the only strategies by which to achieve sustainable manufacturing or improved competitiveness. However, they are a prioritised response to current global trends, government signals and challenges and opportunities for Australian manufacturers. Manufacturing in Australia has reached a crossroad. Tough economic conditions mean in order to survive manufacturers must adapt and respond to competitive pressures by innovating to remain productive and prosperous. This paper provides an overview of the drivers, enablers and an example for each innovation response. This clearly demonstrates the link between innovation and sustainable manufacturing and how innovation can provide a competitive advantage.

Keywords:

Australia, Innovation, R&D, Resource Efficiency, Sustainable Manufacturing

1 INTRODUCTION

The previous two years have seen a focus like never before on the future of manufacturing in Australia. An increasingly challenging economic environment is the consequence of many factors, including the high Australian dollar which has had near parity with the US dollar between December 2010 to June 2013. Rising resource costs have also placed pressure on manufacturers to remain competitive. In October 2011, the Australian Prime Minister convened a taskforce on manufacturing to map a vision for the future of manufacturing in Australia as it adjusts to economic pressures and competition from Asia[1]. In December 2011, the Commonwealth Scientific Industrial Research Organisation (CSIRO) held an industry workshop to discuss 'What sustainable manufacturing means to Australia'[2]. This paper takes into account the current global trends as well as government and industry signals to describe the innovation priorities for sustainable manufacturing in Australia. Innovation is a key lever by which to address the challenges of manufacturing while becoming more economically, socially and environmentally viable. This paper describes 3 sustainable manufacturing innovation priorities; resource efficiency, new technology and business model innovation. For each innovation priority, a driver, enabler and example are provided. The author proposes that the three innovation priorities described in this paper are critical in enabling a transition to sustainable manufacturing in Australia, and further, that they provide a competitive advantage in today's challenging times. These innovations are not the only source of competitive advantage for manufacturing firms. For example, improving skills, diversification and the ability to enter new supply chains are also sources of competitive advantage.

2 CONTEXT AND DEFINITIONS

2.1 The current state of manufacturing in Australia

Manufacturing makes a vital and significant contribution to Australia's economy. The sector's contribution to GDP has declined from 9.5% to 8.7% between 2005-06 and 2009-10. In 2010-11, the manufacturing sector employed 991,800 people; this is a decrease from the 1.05 million people employed the previous year, and sadly, over 100,000 jobs have been lost in manufacturing since 2008[3]. In 2010-11, manufacturing accounted for 34% of Australia's total export trade. This has declined steadily since 2006-07 when manufacturing's share of exports was 50%[4]. In 2010-11, the sector contributed to over 27% of total business in R&D expenditure, this is larger than any other sector and equates to a $4,760 million investment in R&D. Further, this increased by $499 million compared to the year prior[5]. Despite the general decline of many economic metrics over the previous few years, manufacturing remains an important part of the Australian economy. It contributes to a diverse economy with both direct and indirect contributions and it supports and enables other parts of the economy such as agriculture, mining, construction and services[3]. In 2006, the Australian Industry Group estimated for every $1 generated by the manufacturing sector this resulted in additional $1.25 expenditure in the rest of the economy[6].

In 2006, the OECD noted the declining contribution of manufacturing to GDP as an ongoing trend across many OECD countries. This reflects the shift of developed economies towards the services sector and an increasing blurring of the distinction between manufacturing and services[7]. As competition with low cost, developing economies continues, this trend may well continue for Australia. The pursuit of sustainable manufacturing innovation objectives will improve competitiveness and may well play a role in differentiating Australian manufacturing from low cost competitors. As such, these 3 sustainable manufacturing innovation priorities may be relevant to other developed nations.

2.2 Definition of Sustainable Manufacturing

Manufacturing can be defined as 'the full cycle of activities from research and development, through design, production, logistics and services, to end of life management' [8]. However, similar to the definition of 'sustainability', there is no common definition for sustainable manufacturing. Most

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

definitions generally adhere to the principles first outlined in the 1987 Bruntdland report, that is: 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs'[9]. Three useful definitions and descriptions for sustainable manufacturing are from the US Department of Commerce, Queensland State Government in Australia and the Organisation for Economic Co-operation and Development (OECD). The US Department of Commerce defines sustainable manufacturing as 'the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound[10].' The Queensland Government describes sustainable manufacturers as those who 'use world-class manufacturing and environmentally friendly practices to improve the profitability of their business and reduce their impact on the environment[11].' Lastly, the OECD defines the general principle of sustainable manufacturing 'to reduce the intensity of materials use, energy consumption, emissions, and the creation of unwanted by-products while maintaining, or improving, the value of products to society and to organizations[12].'

2.3 The nexus of sustainable manufacturing, innovation and competitiveness

There is a strong connection between sustainable manufacturing, innovation and increased competitiveness. It is important to note that the OECD also relates the term 'sustainable manufacturing' to 'eco-innovation'[13]. The latter is described as the trigger to developing a green economy and assist manufacturing to become sustainable. The connection between sustainable manufacturing and eco-innovation underscores the important role of innovation in transforming traditional manufacturing processes to a more sustainable paradigm.

Innovation can assist manufacturers through both the incremental evolution of current practice and the development and application of disruptive technologies which enable fundamental change to manufacturing and markets. Whilst research and development (R&D) plays a significant role in the process, innovation extends beyond R&D. Within Australia, a commonly used definition of innovation is: 'Innovation is the implementation of a new or significantly improved product (good or service), process, new marketing method or a new organisational method in business practices, workplace organisation or external relations[14]'

It has been proven that innovation is also connected with increased firm competitiveness and success. The 2012 Australian Innovation Systems report provides clear evidence that innovation active companies are more competitive as they are:

- 41 per cent more likely to report increased profitability,
- Twice as likely to report increased productivity,
- Twice as likely to export, and
- Up to four times more likely to increase employment and social contributions[15].

Innovation is needed for sustainable manufacturing, and in turn, the pursuit of both objectives have a high liklihood of influencing firm competitiveness. The following section describes the 3 strategically important innovation priorities for sustainable manufacturing.

3 RESOURCE EFFICIENCY

3.1 Driver - the global megatrend 'more from less' and environmental regulations

In 2010, CSIRO first published a report on Global Megatrends. This was well received by industry and of the 6 trends described, 'more from less' resonated greatest with manufacturers. It is testament to this persistent trend that when the CSIRO updated its global megatrends for 2012, 'more from less' remained and was simply updated with more recent data. This megatrend describes the depletion of our natural resources occurring at alarming rates while the impact of population growth and climate change will continue to increase pressure on resource demand[16]. Examples of data supporting this megatrend are; by 2043 our global population will reach 9 billion people, global food production needs to increase by 70% between now and 2050 in order to meet demand, global water demand will rise by 55% between 2000 and 2050 with manufacturing a key driver of this increased demand, global energy consumption will rise by 40% between 2009 and 2035, mineral ore grades are declining while ore production is increasing.

Manufacturing provides goods and services that support our quality of life and the economy. It has historically been based on the paradigm of unlimited resources [17]. The folly of this assumption, and the forces of the 'more from less' megatrend, make resource efficiency a priority for achieving sustainable manufacturing. Resource efficiency also provides Australian manufacturers with a competitive advantage by reducing costs and increased productivity.

Another driver of resource efficiency and increased manufacturer responsibility is product stewardship. This expands the responsibility of manufacturers to include responsible disposal of their products. Regulation has successfully been implemented in Europe and in 2011, Australia implemented the Product Stewardship Act which provides a framework for regulatory, co-regulatory and mandatory product stewardship. The aim of the Act is to reduce waste sent to landfill and increase recovery and recycling rates. Product stewardship now applies in Australia for televisions, computers, mercury containing lights and tyres[18].Future opportunities exist for manufacturers that reduce the environmental footprint of their products and processes and differentiate based on their whole of life impacts [8].

Environmental regulations in Europe, such as the Registration, Evaluation, Authorisation and Restriction of Chemical substances (REACH) and the UK Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) demand increased transparency of product information and its impact on human health and the environment[19]. These types of environmental regulations support the development of global green supply chains and have the potential to restrict trade of noncompliant Australian products.

3.2 Enabler – investment to support resource efficient manufacturing

The Australian manufacturing sector was the third largest consumer of electricity in 2009-10[20]. Emissions intensity varies across the manufacturing subsectors and the plastics sector is ranked 9th. Despite this low rank, the Plastics and Chemicals Industry Association (PACIA) reported electricity costs for small to medium enterprises (SME) equates to between 2-18% of input costs [21]. As a result, energy costs and energy efficiency are a key concern for Australian manufacturers.

Australia has historically benefitted from low energy prices. This is changing as resource costs rise and accounting for carbon emissions becomes part of the economy. The Australian government has committed to the long term target of reducing 2000 level emissions by 80% by 2050. This is consistent with targets announced by the United Kingdom and Germany. In the short term, Australia will reduce carbon pollution by 5% from 2000 levels, by 2020[22]. To achieve this, Australia implemented a carbon price on 1 July, 2012 as part of its Clean Energy Future policy. Under this program, support for the manufacturing sector includes $1.2 billion to improve energy efficiency and research and development for low carbon technologies. Government investment is enabling the transition towards more resource efficient and competitive manufacturing in Australia.

The increased constraints on resources, whether as a result of higher price or declined availability, will inevitably necessitate manufacturers becoming more efficient with their resources. In the future, manufacturers will continue to reduce waste of all types, through resource recovery, closed loop manufacturing, industrial symbiosis or industrial ecology.

The application of industrial ecology is embroyonic in Australia. The most well known example is the Kwinana Industrial Area in Western Australia. Industrial ecology has been noted as having the potential to improve sustainable manufacturing[23]. The 2013 New South Wales (NSW) Government Waste and Resource Recovery Initiative has recognised the potential of industrial ecology by prioritising the establishment of 4 industrial ecology networks as part of its Business Recycling Program[24]. The uptake of industrial ecology or symbiosis marks a turning point in strategic waste management as it supports both environmental goals to reduce waste to landfill and industry goals to improve resource efficiency. The NSW Government commitment is another example of investment that supports resource efficient manufacturing.

3.3 Innovation Example - Biofiba®

The CSIRO has many examples of applying R&D to develop resource efficient manufacturing processes. A recent example is the research collaboration with the company Biofiba® Ltd, a NSW based SME. A novel process takes fibres from commercially grown hemp and combines them with starches and binding agents to make a composite. This unique composite can be extruded into planks that are able to be drilled and nailed together into a bio-composite pallet[25]. The pallet is designed to decompose rapidly into a potentially valuable garden mulch product. The benefits of this pallet are:

- cost-effective process
- a strong, durable product
- sterile material removes the need for heat or chemical fumigation treatment
- minimal waste – planks manufactured to specific lengths
- bioderived, biodegradable end product[25].

If the technology is successfully scaled-up, Biofiba® will be ideally positioned to capture a portion of the USD$90 billion dollar export pallet market. In recognition of this novel process and product, Biofibre® was a finalist and runner up in the 2012 Australian Cleantech competition.

A second example is CSIRO's zero waste powder coating for plastic automotive components. This process replaces traditional wet paints, reduces waste, eliminates harmful chemical emissions and saves cost, energy and greenhouse gas emissions[26].

4 BUSINESS MODEL INNOVATION

4.1 Driver – The rise of the services economy

The provision of manufacturing services can be described as 'additional services to complement a tangible product offering in order to add value'[27]. This denotes a shift to a product-service relationship with customers, creating lengthier relationships, potentially excluding competitors and producing more reliable revenue streams[27, 28]. Globally, an average manufacturing services firm has around 30% of sales as services[29]. In Australia, the services economy delivers around 80% of GDP and employs 85% of the workforce[30]. Moreover, around 23% of Australian manufacturing companies already provide a service, and some companies that do so are already classified within the services sector[31]. The CSIRO megatrend 'Great Expectations' is consistent with the gradual shift towards service offering from manufacturers. It describes the rise in expectations for personalised services, the increase in demand for experiences over material consumption and the rise in moral and ethical expectations for consumer products[16].

4.2 Enabler – NBN and service innovation

An enabler for business model innovation, such as developing manufacturing services, could be the upgrade of Australia's telecommunications infrastructure and implementation of National Broadband Network (NBN). At a CSIRO workshop in December 2011, industry participants expected the NBN to assist in supporting globally connected businesses, and new opportunities for services and exports[2].

Manufacturing services also support sustainable development, and the transition to sustainable manufacturing, through the dematerialisation of society[28]. The World Business Council for Sustainable Development identified service extension as a key aspect of eco-innovation, responsible for extending product life and reducing turnover[29]. Within traditional firms, the transition to services is enabled by business model or design led innovation. However, the transition to services does pose challenges to many manufacturers through lack of:

- senior management support,
- information technology,
- organisational design,
- appropriate capabilities,
- and culture[29].

4.3 Innovation Example – industry examples and the Australian Design Integration Network

There are opportunities to improve profitability through business model innovation by the application of design led innovation. An Australian example of business model innovation is from the mining sector. High value service provision occurs in exploration and customer solutions e.g. Orica Mining Services. Benefits include a higher margin business model[15]. Another example is the award winning plastic recycling scheme implemented by Tapex who manufacture plastic products for the Agriculture sector. Tapex created a market for recycled plastic by introducing a cost effective program to capture all farm plastics, regardless of type or manufacturer. Recycled plastic is remanufactured into products, such as tiles and compost bins[32]. This closed loop solution provided improved customer service, developed a new brand, market and products. It is an example of business model innovation resulting in improved resource efficiency.

In March 2013, CSIRO participated in establishing the Australian Design Integration Network (ADIN). The network was launched with partners across the national innovation system to address 2 key gaps; the lack of a research base to support design led innovation in Australia and the lack of collaboration in design led innovation across Australia's innovation system[33]. The aim of the ADIN is to explore the role and value of design led innovation in Australia, particularly for the benefit of manufacturers. The ADIN will support business model innovation, creativity and innovation within the manufacturing sector.

5 NEW TECHNOLOGY

The imperatives for manufacturing in Australia range from a transition to high value, high tech manufacturing to more recently, smarter manufacturing for a smarter Australia[3]. Both are a recognition that Australia cannot compete with the low labour costs in developing countries in an increasingly high cost economic environment. The Australian government acknowledges that value adding through access to knowledge and technology is an important factor in the future of Australian manufacturing[34]. Value adding could be achieved by investment many types of technologies, for example clean technologies, lightweight robotics or additive manufacturing, and is dependent on firm needs.

Alongside the need to value add to manufactured products and transition to delivering sustainable, high tech manufacturing, is the gradual shift from mass production of goods to mass customisation. This was reported by CSIRO to the Prime Minister's taskforce on manufacturing as of increasing importance to Australia[3] and this is enabled by disruptive technology such as additive manufacturing.

5.1 Driver - Competing in the Asian Century

A major trend of direct importance to Australian manufacturing is the rise of Asia. The scale of growth and transformation in Asia was the driver behind the Australian Government's White Paper on Australia in the Asian Century. This paper will help position Australia through the recommendation of actions and policy initiatives to position Australia for the Asian Century[35].

Forecast Asian growth is referred to as 'The Silk Highway' in the CSIRO 2012 megatrends report. Data supporting this megatrend are: by 2025, Asia will account for over half of the world's economic output [35], over a billion people will transition from poverty to the middle class influencing global demand for goods and services, the 2012 five year economic outlook forecasts 8% per annum growth for Asia compared to 2-3% growth for advanced economies, China has strong economic links with Australia as its largest trading partner, China accounts for around 20% of the world's population[16].

Another driver is to add value to Australia's natural resources such as titanium ore. Australia has the world's greatest reserves of titanium ore, much of which is being exported without domestic processing. It is estimated that at current rates, Australia has 90 years of titanium resource remaining. The value of titanium alloy metal is 100 times the market value of ore. If Australia were to grow its domestic processing industry and convert ore to metal then it could theoretically extend the life of the ore and add significant value to exports [8]. New technology processes and additive manufacturing technologies will enable Australia to develop high tech, high value manufacturing opportunities in titanium products.

5.2 Enabler – additive manufacturing technology

Additive manufacturing (AM) is sometimes referred to as 3D printing and has evolved from rapid prototyping to become a disruptive technology with application for the manufacturing, aerospace, health and infrastructure sectors. It works by depositing material layer by layer onto a substrate. AM technologies differ in the type of material used and the bonding technique applied [36]. The general advantage of AM is it uses less energy, produces less waste and can create more complex products that are unable to be produced through traditional methods [37]. AM can also increase speed to market, time to manufacture and reduce costs [38]. These benefits are aligned with the earlier definitions of sustainable manufacturing.

AM is often referred to as a disruptive technology as it has the potential to create new markets and products, and realise a shift from mass production to mass customisation. It has been referred to as the next industrial revolution for manufacturing in advanced economies as it has the potential to provide competitive advantage that is not based on low labour costs. This may result in manufacturing returning to developed economies like Australia and the USA, with products produced close to markets. A key enabler to leveraging this technology for competitive advantage are capability strengths in designing and engineering fit for purpose parts and products[39].

Despite the attractiveness of the technology there are some challenges that remain to be overcome, for example;

- security of designs and intellectual property [38]
- parts are constrained by machine size [40]
- the high costs of technology, equipment and materials [37]
- product surface imperfections [37]

Some of these challenges create R&D opportunities to develop cost effective, fit for purpose products with additive manufacturing technology.

5.3 Innovation Example – Victorian Direct Manufacturing Centre

The CSIRO has identified additive manufacturing as a key opportunity for Australian manufacturers to leverage both competitive advantage and the comparative advantage of Australia's natural mineral endowment. An innovation example for AM technology is the CSIRO Victorian Direct Manufacturing Centre (VDMC). It was originally established in 2010 and in 2013, secured additional funding from the Victorian Government and industry partners to continue for another 3 years. The centre applies cold spray additive manufacturing technology to provide benefits for a number of industry partners across a number of applied research projects. The key benefits for the industry partners to date have been:

- reduced production costs
- increased design capability
- greener production processes

- more flexible production lines
- reduced material waste.

These benefits not only align with the definitions for sustainable manufacturing but provide the basis upon which to build a more competitive and sustainable Australian manufacturing industry. As such, AM technology is a strategically important innovation priority for Australia.

6 SUMMARY

The business case for innovation is clear; manufacturing firms cannot prosper based on a business as usual approach. They must respond to the competitive pressures brought about by globalisation and low cost competition. All 3 innovation strategies contribute towards greater sustainability for manufacturing in Australia by improving economic, environmental and social conditions. For example, improved resource efficiency can reduce input costs. Business model innovation can result in new market opportunities and value add to firms. New technologies can similarly create new product and market opportunities while also reducing business costs. These innovation strategies may also be relevant to other developed nations.

Each of the strategies are also interconnected, for example :

- New technology development can result in greater resource efficiency as in the case of Biofiba®.
- Business model innovation can be driven by new technologies as the case for Additive Manufacturing.
- Resource efficiency opportunities can be developed by applying business model innovation as demonstrated by the Tapex example.

Each strategy also contributes to the common elements in the definitions of sustainable manufacturing. These are; reducing environmental impact, conserving energy, applying world class manufacturing and improving the profitability and value of products to society and organisations.

7 CONCLUSION

Australian manufacturers are seeking opportunities to become more competitive. Innovation is a critical lever to achieving increased competitiveness and this is linked to sustainable manufacturing. The 3 examples described in this paper prioritise innovation strategies for industry. These are not the only strategies by which to achieve either sustainable manufacturing or increased competitiveness. However, they are the author's view of the most important innovation priorities for Australian manufacturers based on global trends, government signals, industry challenges and opportunities. These strategies are part of the solution to addressing the decline currently occurring in Australian manufacturing. Each strategy has the potential to improve competitiveness and supports the goals of sustainable manufacturing for Australia.

8 ACKNOWLEDGMENTS

The author extends sincere thanks to all who provided constructive feedback on this paper.

9 REFERENCES

1. Australian Government. *About the Prime Minister's Taskforce on Manufacturing*. [Date viewed 23 March, 2013]; Available from: http://www.innovation.gov.au/Industry/Manufacturing/Taskforce/Pages/AbouttheTaskforce.aspx.
2. King S, *What does Sustainable Manufacturing mean to Australia?*, 2012, CSIRO.
3. Australian Government, *Prime Minister's Manufacturing Taskforce - Report of the Non-Government Members,* 2012, I. Department of Industry, Science, Research and Tertiary Education: Canberra.
4. Australian Bureau of Statistics, *Year Book Australia, 2012,* 2012, A.B.o. Statistics: Canberra.
5. Australian Bureau of Statistics. *Research and Experimental Development, Businesses, Australia, 2010-11*. [Date viewed 7 March, 2013]; Available from: http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/8104.0Main%20Features22010-11?opendocument&tabname=Summary&prodno=8104.0&issue=2010-11&num=&view=.
6. Australian Industry Group, *Manufacturing Futures - Achieving Global Fitness,* 2006, Australian Industry Group: Sydney.
7. OECD, *The changing nature of Manufacturing in OECD economies,* 2006, OECD: Paris.
8. Australian Government, *Trends in Manufacturing to 2020 - a foresighting discussion paper,* 2011, I. Department of Innovation, Science and Research: Canberra.
9. Brundtland, G., *Our common future: Report of the 1987 World Commission on Environment and Development*, 1987, Oxford: Oxford University Press.
10. United States Department of Commerce. *How does Commerce define Sustainable Manufacturing?* [Date viewed 7 June, 2013]; Available from: http://trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp.
11. Queensland Government. *Sustainable Manufacturing*. [Date viewed 5 May, 2013]; Available from: http://www.business.qld.gov.au/industry/manufacturing/sustainable-manufacturing.
12. OECD, *Overview of the OECD Sustainable Manufacturing Toolkit Prototype,* 2009, OECD: Paris.
13. OECD, *Sustainable Manufacturing and Eco - Innovation, Framework, Practices and Measurement* 2009, OECD: Paris.
14. OECD, *Oslo Manual Guidelines for collecting and interpreting innovation data,* 2005, OECD and European Commission: Paris.
15. Australian Government, *Australian Innovation System Report 2012,* 2012, Department of Industry,

Innovation, Climate Change, Science, Research and Tertiary Education: Canberra.

16. Hajkowicz, S., H. Cook, and A. Littleboy, *Global megatrends that will change the way we live. The 2012 revision,* 2012, CSIRO: Canberra, Australia.
17. Garetti, M. and M. Taisch, *Sustainable manufacturing: trends and research challenges.* Production Planning & Control, 2012. **23**(2-3): p. 83-104.
18. Australian Government, *Product Stewartship Act 2011 - Fact Sheet,* 2011, E. Department of Sustainability, Water, Population and Communities: Canberra.
19. Cook, H., et al., *Elements in Everything: Current profile and future trends for the Australian plastics and chemicals industry.,* 2013, CSIRO: Canberra.
20. BREE, *Energy in Australia 2012,* 2012, E.a.T. Department of Resources: Canberra.
21. PACIA, *Submission to the CPRS Green Paper (PACIA).* 2008.
22. Australian Government, *Securing a clean energy future - The Australian government's climate change plan* 2011, Department of Climate Change and Energy Efficiency: Canberra.
23. Roberts, B.H., *The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study.* Journal of Cleaner Production, 2004. **12**(8–10): p. 997-1010.
24. NSW Government, *Waste Less, Recycle More: A five-year $465.7 million Waste and Resource Recovery Initiative,* 2013, N.E.P. Authority: Sydney.
25. CSIRO Future Manufacturing Flagship, *BioFiba®—a biodegradable timber replacement*, CSIRO, Editor 2012: Canberra. p. 2.
26. CSIRO. *Zero-waste coating process a real winner*. [Date viewed 23 May 2013]; Available from: http://www.csiro.au/en/Organisation-Structure/Flagships/Future-Manufacturing-Flagship/Agile-Manufacturing/Intelligent-Manufacturing-Technologies/Zero-waste-coating-process-a-real-winner.aspx.
27. Wilkinson, A., A. Dainty, and A. Neely, *Changing times and changing timescales: the servitization of manufacturing.* International Journal of Operations & Production Management, 2009. **29**(5).
28. Winroth, M. and G. Johansson. *A lean perspective on servitization of manufacturing*. in *Proceedings of the POMS 22nd Annual Conference*. 2011.
29. Visnjic, I.a.V.L., Bart,, *Servitization: Disentangling the Impact of Service Business Model Innovation on the Performance of Manufacturing Firms.* ESADE Business School Research Paper, 2012. **No. 230**.
30. Australian Government, *Australia - Europe Brief,* 2011, A.T. Commission: Canberra.
31. Roos, G., *Manufacturing into the future,* 2012, Department of the Premier and Cabinet: Adelaide.
32. Hajkowicz, S., et al., *Strategic Directions: Towards sustained growth of the Australian chemicals and plastics industry,* 2013, CSIRO: Canberra.
33. CSIRO. *Design-led innovation*. [Date viewed 5 May, 2013]; Available from: http://www.csiro.au/en/Organisation-Structure/Flagships/Future-Manufacturing-Flagship/Agile-Manufacturing/Sustainable-Manufacturing-Innovation/Design-led-innovation.aspx.
34. Australian Government, *An Overview of the Clean Energy Legislative Package,* 2012: Canberra.
35. Australian Government, *Australia in the Asian Century,* 2012, Australian Government: Canberra.
36. Gibson, I., D.W. Rosen, and B. Stucker, *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. 2009: Springer.
37. Huang, S.H., et al., *Additive manufacturing and its societal impact: a literature review.* The International Journal of Advanced Manufacturing Technology, 2012.
38. Berman, B., *3-D printing: The new industrial revolution.* Business Horizons, 2012. **55**(2): p. 155-162.
39. Campbell, T., Williams, C., Ivanova, O., Garrett. B, *Could 3-D Printing Change the World?,* 2011, Atlantic Council Strategic Foresight: Washington, D.C.
40. Igoe, T.M., Caterina *A Strategist's Guide to Digital Fabrication*. 2011.

1.5 Modeling of enterprise investment activity, taking into account an environmental factor

A. Borlakova

Modeling of economic and information systems Department, Financial University under the Government of the Russian Federation, Moscow, Russia

Abstract

The modern economy is becoming more dependent of environmental standards and orientation on international concept of sustainable development.

The most important condition on the way of economy transition to an innovative way of development is preservation of human vital activity-environment system equilibrium. Significant role in achievement of the country's economy strategic objectives performs investment activities, which affects not only the conditions of human vital activity, but also on the ecologo-economic system state.

At the paper, necessity to taking into account an environmental factor in the process of investment projects estimation is defined.

The projects efficiency criteria are suggested to calculate using the elements of the fuzzy sets theory, by mean of which many uncertainties factors may be formalized and correctly considered in the estimation process. The approach promotes objective justification of the investment decision.

Keywords

Fuzzy set, ecologo-economic estimation, investment project, sustainable development.

1. INTRODUCTION

One of the most pressing challenges on the way to sustainable manufacturing is necessity to improve of the enterprises investment activity, taking into account environmental aspects.

At a market economy conditions in the enterprise investment activities management system must be considered a complex of factors that influence the decision on the amount and structure of capital investments.

Consider the features of the enterprises investment activity improvement in the direction of strengthening its orientation to the solution of environmental problems.

2. ENVIRONMENTAL FACTOR IN ECONOMY

2.1 Economic factor of ecological information

Consider the generalized index, which would reflect the economic importance of ecological information [2, p. 54; 7, p. 56-57].

Assume I_t - volume of ecological information, which can be objectively received at the t moment of time, and I_u - the volume of this information, used in national economy. Then the relation of $K_{ec} = I_u/I_t$ represents the demand coefficient of ecological information.

On the fig. 1 qualitative dependence of K_{ec} from one of the most important economic indicators –gross domestic product per capita is shown (GDP/N_p, N_p - population size).

K_{ec} increases at growth of specific GDP, i.e. growth of society welfare is inevitably connected with increase of the ecological information weight, used in national economy. Two conclusions can be done.

First of all, there is inverse monotonously increasing functional dependence of GDP per capita on the economy's demand for K_{ec} ecological information (fig. 2) owing to the K_{ec} function monotonicity.

It means that the GDP growth is directly connected with improvement of society activity conditions and environment.

Secondly, ecological information starts to play an appreciable role as object and an element of information business only from a certain stage of the country economic development.

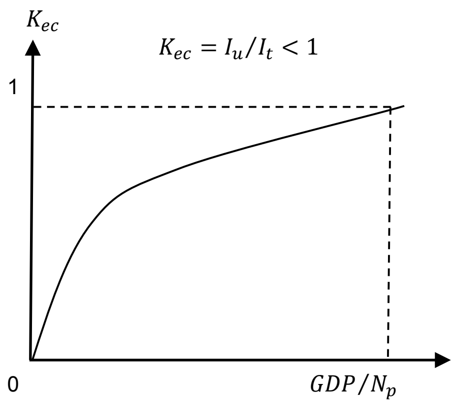


Figure 1: Qualitative dependence of K_{ec} from GDP per capita.

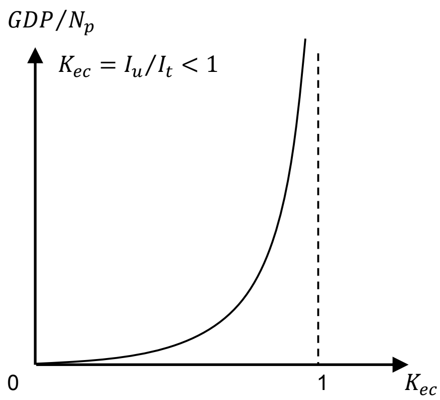


Figure 2: Functional dependence of GDP per capita on the economy demand for K_{ec} ecological information.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

2.2 Database of ecological information

The scheme of a two-level database of ecological information is shown on fig. 3 [2, p. 51].

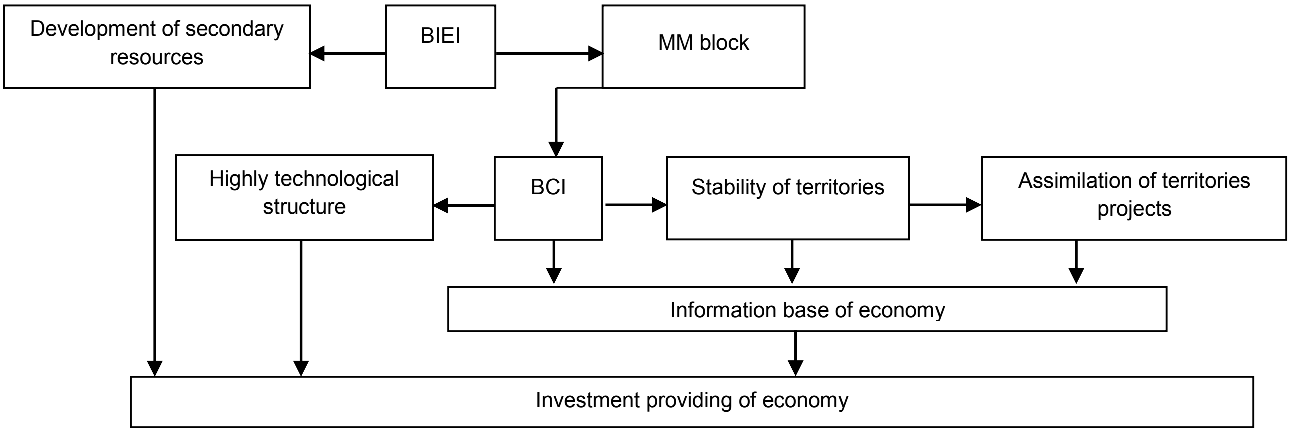


Figure 3: Two-level database of ecological information.

Information should be prepared and adapted for use in the corresponding mathematical models of ecologo-economic systems. Should be two interconnected levels:

- primary ecological information on a natural and technogenic situation of territories (base of initial ecological information – BIEI). It also includes information about the limits of specific locations environmental sustainability in the most characteristic of them natural processes;
- such database, tariffing the regions, with participates in the micro economical communications, as objects of possible technological development with a certain framework (base of calculating information – BCI) created on the first level ecological information basis through the math models (MM) complex.

2.3 Management of environment

The environment management efficiency depends of the enterprise readiness to conduct systematic management of environment.

The enterprise, which control system includes management of environment, possesses a basis for a balancing of economic and ecological interests and can reach considerable advantages in the competition. The potential benefits connected with effective management of environment, include:

- support from the state and the public;
- satisfaction to ecological requirements of investors and expansion of access to the capital;
- improvement of reputation and increase in a market share.

The model of enterprise environment control system is presented on the fig. 4 [1]:

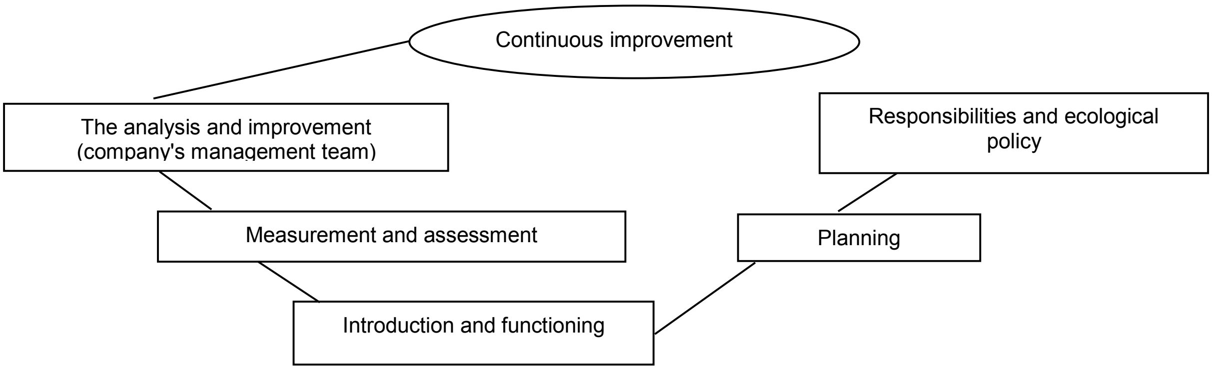


Figure 4: Model of environment control system.

The model consists of the following basic elements:

1. *Ecological policy.* The enterprise should define the ecological policy and incur responsibilities concerning management of environment.
2. *Planning.* The enterprises should create the plan of the ecological policy realization.
3. *Introduction.* The enterprise should create possibilities and the mechanisms, necessary for implementation of their ecological policy and achievement of planned ecological indicators.
4. *Measurement and assessment.* The enterprise should measure, supervise and estimate the ecological efficiency.
5. *Analysis and improvement.* The enterprise should analyze and constantly improve the environment control system.

3. COMPLEX APPROACH TO INVESTMENT PROJECTS EVALUATION

At the market economy conditions in the management of enterprise investment activity should be considered a complex system of factors, influencing to decision on the amount and structure of capital investments. Among the many factors, defining of the company investment strategy, the main are economic and financial, sociopolitical and legal, and environmental factors too [3, p.82].

There are the following reasons of environmental factors consideration in the evaluation of investment projects:

- ✓ complexity of many factors impact on the environment accounting due to their diversity;
- ✓ absence of methods that allow to give a complex evaluation of the investment projects efficiency;
- ✓ weak institutionalization of relations in the sphere of compensation for damage, caused to the environment.

These circumstances cause necessity of ecologo-economic evaluation of investment projects methodology development.

Such assessment would allow to determine project performance indicators and to draw conclusions about its desirability and feasibility by means of calculation consequences of impact on the environment in monetary terms.

Use of this methodology will allow to evaluate and grade the investment projects, depending on the environmental equilibrium level and economic efficiency.

At the fig. 5 algorithm of the investment projects ecologo-economic evaluation is shown.

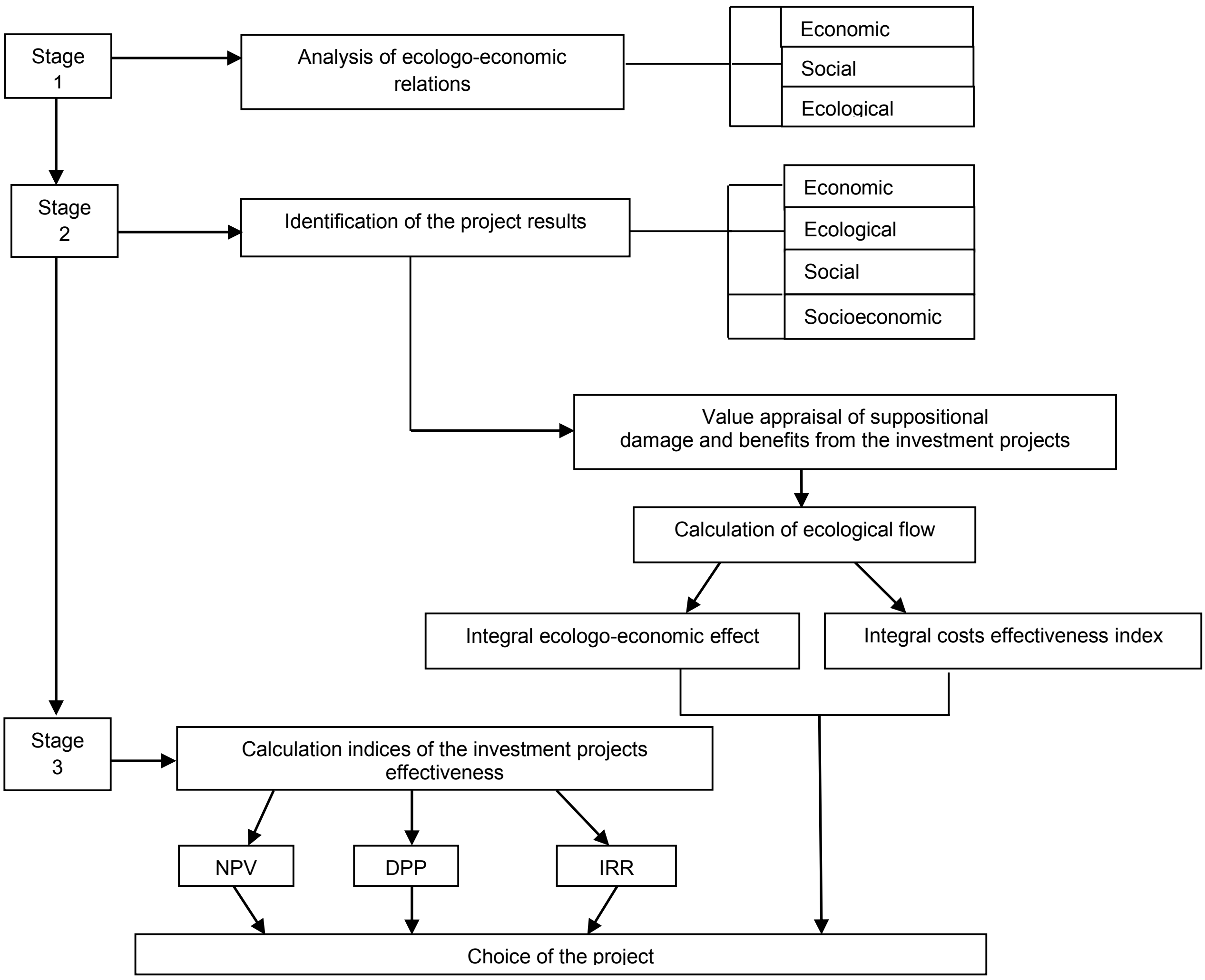


Figure 5: The algorithm of the investment projects ecologo-economic evaluation

3.1 Valuation of suppositional damage and benefits from the investment projects realization

Consider in more detail the second stage of algorithm. After identification of the projects results, valuation of suppositional damage and benefits is carried out.

Understanding of the project ecological component valuation is based on the components such as operating and investing activities. Because investments on implementation of environmental protection - is an element of a cash flow from investing activities, and operating costs of environmental protection equipment - an element of a cash flow from operating activities.

Accumulation in one cash flow of environmental support of the project costs, and then defining environmental impacts, both positive and negative, in value terms, will allow [5, p. 64-72]:

- ✓ identify the dependence between the ecological costs volume and volume of ecological results;
- ✓ determine the optimal level of said indicators ratios to achieve adequate level of the project environmental safety;
- ✓ determine integral indicators of the ecological costs efficacy.

Consider the method of investment project ecological flow calculation [5, c. 64-72].

Ecological flow value is calculated as:

$$F_t^e = I_t^e - O_t^e, \quad (1)$$

where I_t^e is environmental component of cash inflow;

$O_t^э$ is cash outflow;

t is a step number of calculation, which takes values from 0 to T.

The positive impact of the project on the environment contributes to following benefits (B_t^e):

- ✓ production output is increased due to development of the recycling of wastes system;
- ✓ the market of environmental works and services is expanding;
- ✓ investment prospects of the region or industry is increased.

We can distinguish the investment and operating costs for the environmental character measures implementation by means of the cash outflows $O_t^э$ environmental component consideration.

A conditionally suppositional damage valuation D^{CAD} is accepted as a value of the ill environmental effect.

Conditionally suppositional damage - is the valuation of potential losses and negative changes in the environment due to investment project implementation. Depending on the loss wording and the object influence characteristics, it can be identified economic, ecological, social and socioeconomic investment project implications. Thus, the conditionally suppositional damage can be divided into economic, ecological, social and socioeconomic.

Conditionally suppositional economic damage D^{CAE} - is the loss of products, services, equipment, fuel, energy, raw materials and other materials as a result of waste and irrational resources use.

Conditionally suppositional ecological damage D^{CAECO} - refers to a state of ecological systems and natural resources.

Conditionally suppositional social damage D^{CAS} – represents increase of psychological stress on the population; decrease in length and quality of life.

Conditionally suppositional socioeconomic damage D^{CASE} - is the costs for social security and health care, due to increasing incidence as result of environmental pollution.

To determine the social losses the most effective approach the expert evaluations method is used. Experts are asked to estimate the social losses coefficient K^{SL}, which ranges from 1 to 2:

- ✓ 1 – the factor is insignificant for social repercussions of the project;
- ✓ 1,25 – the factor is inessential for social repercussions of the project;
- ✓ 1,5 – expert can't say anything definite about impact of the factor;
- ✓ 1,75 – the factor is essential for social repercussions of the project;
- ✓ 2 – the factor value is obvious and is very essential for social repercussions of the project.

Social losses coefficient K^{SL} is determined by the formula:

$$K^{SL} = \frac{\sum_{m=1}^{M} P_{im}}{M}, \quad (2)$$

where P_{im} is estimation of *i*-th factor value by expert *m*; *M* is number of experts.

Total value of conditionally suppositional damage caused by the investment project can be represented as follow:

$$D^{CAD} = (D^{CAE}) + (D^{CAECO}) + (D^{CASE})K^{SL}. \quad (3)$$

D^{CAD} value should not exceed the conditionally suppositional normative damage ($D^{CAD,norm}$), which is calculated in compliance with normative indicators of environmental quality. To account for the ratio of normative and conditionally suppositional damage in the investment project effectiveness evaluation should be calculated eco-index of the project:

$$I_t^{ECO} = \frac{D_t^{CAD}}{У_t^{CAD,norm}}. \quad (4)$$

If the eco-index value is greater than 1, it means the permitted damages are exceeded. Taking into account (4) eco-flow model can be represented as:

$$F_t^E = I_t^E - O_t^E = B_t^E - [D_t^{CAD} + O_t^E I_t^{ECO}]. \quad (5)$$

Now one can calculate the key efficiency indicators of the investment project, based on the cash flow from investment (F^{IV}), operating (F^{O}) activity and eco-flow (F^{E}), consisting in return, of the project cash inflows (I^{IV}), (I^{O}), (I^{E}) and outflows (O^{IV}), (O^{O}), (O^{E}).

Integral ecologo-economic effect calculated by the formula:

$$E^{IEE} = K^{SL} \sum_0^T \frac{F_t^{IV} + F_t^O + F_t^E}{(1+E)^t}, \quad (6)$$

where *E* is the discount rate. The project will be considered effective if E^{IEE} is a positive [5, p. 64-72].

Integral costs effectiveness index:

$$I^{IEC} = K^{SL} \frac{\sum_0^T (I_t^{IV} + I_t^O + I_t^E)}{\sum_0^T (O_t^{IV} + O_t^O + O_t^E)} \quad (7)$$

The criterion of cost effectiveness is the ratio:

$$I^{IEC} > 1 \quad (8)$$

3.2 Indices of the investment projects effectiveness

Third stage of the algorithm (fig. 5) involves the calculation of indices of the investment projects effectiveness. Companies must evaluate a potential projects maximal qualitative and in a short time at the estimation and choice of the investment projects process. As a rule, the degree of this projects elaboration is very low and therefore, there is limited, inaccurate and incomplete information for them. In such circumstances, it is difficult and inappropriately to use of standard approaches to the projects evaluation, due to lack of information.

In such situation, the most effective is use fuzzy sets theory elements, through which many uncertainties factors may be formalized and properly taken into account [6, p. 559–563]. The fuzzy-multiple methods significant advantages include the possibility of uncertainty accounting not only during the efficiency calculation, but also in the cash flow of the project forming process.

The obvious advantages of the fuzzy sets methods include:

- ✓ the possibility of formalizing the many uncertainties factors, that described by natural language;
- ✓ no requirement to gleichheit form of the membership functions;
- ✓ unlimited number of scenarios for the project development;
- ✓ tools to reduce subjectivity of the expert estimates.

The possibility of using information in the fuzzy form at the investment projects analysis and the construction on the basis of a cash flow provides wide range of information for analysis of the project attractiveness to researcher.

Generally accepted indices of the investment projects effectiveness (*NPV*, *DPP*, *IRR*) need to calculated under condition, that cash flows has a fuzzy form for objective substantiation of the investment decision. And for the most complete analysis it is necessary to present the indices in the crisp and fuzzy form. Consider the methods of *NPV*, *DPP* and *IRR* calculating for the case, when fuzziness of the project parameters is modeled with standard membership functions.

If cash flows represent a fuzzy numbers *net present value* is calculated by the formula:

$$\overline{\overline{NPV}} = \sum_{t=1}^{n} \frac{\overline{\overline{In_t}} - \overline{\overline{Out_t}}}{(1+r)^t}, \quad (9)$$

where $t = 1,2,\dots,n$ is number of periods; $\overline{\overline{In_t}}$, $\overline{\overline{Out_t}}$ are volumes of revenues and expenses respectively presented in the form of fuzzy numbers; r is discount rate (crisp number).

If cash flow components has a membership function standard form, $\overline{\overline{NPV}}$ will also be in the form of fuzzy numbers, because addition, subtraction of fuzzy numbers and dividing by the crisp number does not change the original form of fuzzy numbers.

Also if the discount rate consider as a fuzzy number, the division of fuzzy numbers result does not retain the original standard form. If the discount rate is low, it's possible values dispersion is also small; then the membership function curvature of a fuzzy $\overline{\overline{NPV}}$ is negligible and can be ignored.

Determination of *the internal rate of return* in the classical formulation is to solve for the unknown variable *IRR* equation:

$$\sum_{t=1}^{n} \frac{\overline{\overline{In_t}} - \overline{\overline{Out_t}}}{(1+IRR)^t} = 0. \quad (10)$$

The left-hand side of equation (10) is an fuzzy number, and the right is the crisp number of zero. To be able to correctly perform mathematical operations at the indicator calculation process it is necessary to transform the equation so that right and left sides were agreed.

- ✓ One option is to change the form of the right part, which can be interpreted as a fuzzy zero. This fuzzy zero is characterized in that the maximum degree of membership to this fuzzy number should be zero for crisp number.

Convex fuzzy number A, the base of which is a set of real numbers X, called fuzzy zero if

$$\mu_A(0) = \sup_x(\mu_A(x)). \quad (11)$$

The value of *IRR*, found in the equation (10), can be interpreted as the discount rate at which net present value equal to fuzzy number; the membership function of this fuzzy number reaches a maximum – 1 in a zero number. This approach is easy to use and single-digit in cases, where the triangular fuzzy numbers is operating. If the fuzzy numbers involved at the calculations are complex form, it is supposed to use the second method for calculating the index.

- ✓ The second way is backward transformation - bringing to the crisp form the left side of equation:

$$defuzz\left(\sum_{t=1}^{n} \frac{\overline{\overline{In_t}} - \overline{\overline{Out_t}}}{(1+IRR)^t}\right) = 0, \quad (12)$$

where $defuzz(\cdot)$ is one of the functions that allow compare of the argument crisp value of its value represented by fuzzy number. If cash flows are expressed in fuzzy numbers of standard form, the equation can be solved explicitly. When cash flows are arbitrary fuzzy form, *IRR* is calculated by the exhaustive search of the desired parameter values until is equality in the equation, with a required accuracy, is reached. Calculation effectively carried out using of Matlab software environment.

Thus, the general equation with respect to $\overline{\overline{IRR}}$:

$$defuzz\left(\sum_{t=1}^{n} \frac{\overline{\overline{In_t}} - \overline{\overline{Out_t}}}{\left(1+\overline{\overline{IRR}}\right)^t}\right) = 0 \quad (13)$$

may have more than one solution, and analyst needs an additional condition for the final selection. Such condition can be the function value, which consists of two components, that characterize $\overline{\overline{IRR}}$ fuzzy value. The first component is a defuzzification value of $\overline{\overline{IRR}}$: $defuzz(\overline{\overline{IRR}})$.

This value should be minimized, which corresponds to the classical case of IRR precise meaning estimation, when there is more than one solution of equation (1), from which the minimum value of IRR selected. The second part of the function represented by the component, which formalize a fuzzy set fuzziness measure. Fuzziness measure can be defined as a distance from the fuzzy set A to the nearest crisp set A_0.

A crisp set, nearest to the fuzzy set A with membership function $\mu_A(u)(u \in U)$, is a subset A_0 of the set U, whose characteristic function is determined by the formula [4, p. 26]:

$$\mu_{A_0} = \begin{cases} 1, if\ \mu_A > 0{,}5; \\ 0, if\ \mu_A < 0{,}5; \\ 1\ or\ 0, if\ \ \mu_A = 0{,}5 \end{cases}. \quad (14)$$

A fuzziness measure can be formalized in the functional form described by the formula, using the Hamming distance:

$$\text{fuzziness(A)} = \int_E \left|\mu_A(x) - \mu_{A_0}(x)\right| dx. \quad (15)$$

For the fulfillment of the $0 \le fuzziness(A) \le 1$ condition, the above expression must be divided by the $1/2\int_E\ dx$. A fuzziness measure of the required internal rate of return - $fuzziness(\overline{\overline{IRR}})$ should be minimal. Therefore, the second component of the function, requiring of minimization, can be represented by the following formula:

$$\text{fuzziness}(\overline{\overline{\text{IRR}}}) = \int_R \left| \mu_{\overline{\overline{\text{IRR}}}}(x) - \mu_{\overline{\overline{\text{IRR}}}_0}(x) \right| dx. \quad (16)$$

The *discounted payback period* DPP is the final form of the function, which should be minimized:

$$fuzziness(\overline{\overline{IRR}}) + defuzz(\overline{\overline{IRR}}) \rightarrow min. \quad (17)$$

There are two methods of the payback period calculating.

- ✓ Under the first method, the crisp form DPP for the net cash flow can be determined, based on the comparison of fuzzy numbers method, with using membership function defuzzification value. According to this method, the formula for DPP determining in the case when all the parameters of the project are specified in the fuzzy form, takes the following form:

  $$defuzz\left(\sum_{t=1}^{DPP} \frac{\overline{\overline{In_t}} - \overline{\overline{Out_t}}}{(1+\overline{\overline{r}})^t}\right) = 0, \quad (18)$$

  where DPP is discounted payback period; $defuzz(\cdot)$ is defuzzification function.
- ✓ The second method is constructed on the fuzzy numbers principles of ordering, based on fuzzy relations. Comparison of the $defuzz(\cdot)$ function argument fuzzy values from the left side of (18) with zero can be achieved by comparison of fuzzy numbers. One way is to compare the membership functions maximum values, corresponding to the different variants of $\overline{\overline{NPV}}(DPP)$ fuzzy values mutual relations under different DPP and zero values.

The above methods of the investment projects effectiveness estimation in the form of fuzzy numbers allow to valuate the projects comprehensively with a high degree of information uncertainty about the project implementation.

4. SUMMARY

So, according to the proposed method of ecologo-economic evaluation, based on the investment projects effectiveness indices (*NPV, DPP, IRR*) and also valuation of suppositional damage and benefits from the investment projects realization integral ecologo-economic effect and integral costs effectiveness index selects the investment project.

Thus, the ecologo-economic evaluation of the project is an important investment designing tool.

Businessmen and the government should provide sustainable, environmentally acceptable development by limiting or even eliminating of the investment projects negative impact on the economy, ecology and population by implementing such assessment.

Thus, the problem of improvement the enterprise investment activities, taking into account an environmental factor, should be tackled on a joint of investment management problem and economic aspects of environmental problems, using mathematical models

5. REFERENCES

[1] Gluhov V.V., Lisochkina T.V., Nekrasov T.P., 1997, Economic bases of ecology. - SPb.: Special literature, p. 192

[2] Krass M.S., 2010, Modeling of ecologo-economic systems. – M: INFRA-M, p. 51–57.

[3] Krass M.S., 2012, Model of Connections in the Ecology Human Vital Activity Systems// Vestnik MGTU. Estestvennye Nauki. No 1, p.82.

[4] Nazarov D., Konysheva L., 2011, Fuzzy sets theory. - St. Petersburg: SPb., p. 26.

[5] Nuzhina I., 2010, The investment project effectiveness assessment as a tool of environmental and economic regulation // Regional economics: theory and practice. Finance and credit, № 34, p. 64–72.

[6] Zaboev M.V., 2008, Characteristics of different types of uncertainty // Problems of Modern Economics. - St. Petersburg: SPb., No 3, p. 559–563.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

1.6 Investigating short term strategies in product sustainability index implementation, a case study at IKEA

E.Komassi[1], R. Pal [1]
[1] Swedish school of textiles, University of Boras, Boras, Sweden

Abstract
Companies are aware of long term benefits of sustainability, and that in the future the competitive landscape will change. However, financial concerns slow down the sustainability development process.
This article aims to explore how companies move toward long term benefits of sustainability without compromise in their financial objectives in short term. This study focuses on investigating how companies use sustainability index tool as a component of short term strategy.
Findings indicate that companies try to simplify the sustainability assessment and combine it with other decision making tools. This simplification is toward finding potential improvements in the product level. Results are summarized in a model which corresponds to the short term strategy development process toward sustainability. This model describes how company identifies critical products based on financial, strategic and sustainability aspects. The investigation has been performed at children's IKEA in Sweden.

Keywords:
Critical products; Product sustainability index; Strategy; Sustainability implementation; model

1 INTRODUCTION

Due to the increase of customers awareness and their demand for more sustainable products, tougher legislation and limits in resources, companies have started to embrace environmental sustainability [1-4]. There is no way to ignore the important role of manufacturing industries in transformation toward sustainability [5] and there are long term financial and non- financial benefits for companies that adopt sustainability initiatives[6-8] Despite the foregoing, most companies have not moved toward sustainability [9] or "Sustainability is still separated from core business development" [10].

The major issue which slows down the process of adopting sustainability initiatives is not the lack of proper technology or materials, the reason is that companies find it difficult to compete with other rivals who have not invested in sustainable products [11]

Sustainability has been an important issue in IKEA in many aspects but recently sustainability is considered as the forth cornerstone in IKEA's business to be integrated in long term strategies [12].

The purpose of this study is to model the company's approach in implementing sustainability tool. This model describes how company narrows down product categories to reach critical products.

Results indicate that company's strategy in short term is focused on finding critical products using the sustainability assessment tool.

1.1 Sustainability Product Scorecard

SPS, Sustainability Product Scorecard, is a tool developed by IOS (IKEA of Sweden) in order to measure sustainability and classify the products in two groups of more sustainable and less sustainable. SPS consists of eleven weighted criteria, Eight of which are directly related to the product itself and the other three are related to suppliers [12]

2 RESEARCH METHODOLOGY

In order to fulfil the research objective, an initial exploratory research is carried out. This approach helps to have a comprehensive view of the current situation of the company.

This case study is a combination of quantitative and qualitative analysis of the obtained information. Both qualitative and quantitative analyses are interrelated and support each other in different stages of the study. In some stages of the research the results of quantitative analysis have been used as input data for the qualitative analysis.

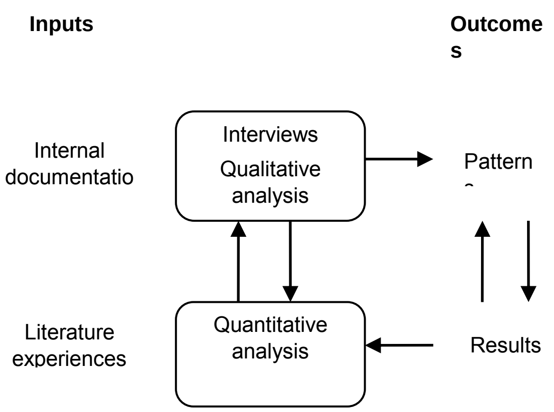


Figure 1: Example of picture scanned into the paper.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

A literature review has been conducted on similar cases where sustainability is being implemented, and the results are used as another input for this research. The sustainability index is a rather young tool in this case. The organization is not completely adapted to it, and there are lots of information sources connected to this tool which are not perfectly organized. Therefore, the nature of this study is exploratory and the undertaken methodology provides a frame for evolving the questions in interviews and systematic use of qualitative and quantitative information. Additionally, this framework is less time consuming and helps to avoid being locked in unnecessary information or detail.

2.1 Interviews and document review

The conducted interviews are structured and unstructured interviews. The advantages of unstructured interviews are supporting the exploratory approach of the thesis, and also providing an open dialogue. Quantitative analysis has taken advantage of grounded theory in categorizing information and finding patterns and relationships.

Figure 1 gives an overview of the method used to complete this research.

3 BACKGROUND

When it comes to implementing sustainability, there are three major dimensions that companies would like to focus upon: measuring sustainability, prioritizing between potential investment for improvements, and simplification of tactics and strategies toward sustainability [9].

It is stated in literature that if companies really intend to support sustainability development they should align and integrate tools and methods for sustainable product development into the general decision-making process [4, 13-17].

It is suggested that companies should integrate sustainability into their business, and support goals with decision making tools. It is crucial to have a strategic platform toward creating a win-win-win situation in which, customers are satisfied with the prices, environmental impact decreases and company does not compromise on financial objectives [4]. This strategic approach will help companies to decrease the chance of sudden costs [10]. It is stated in literature that setting the goal is the prerequisite to be able to be strategic [9, 18]

Case studies and ongoing sustainability projects in companies show that in first steps of sustainability adoption, companies try to simplify the life cycle of products and focus on the most important stages of life cycle [19-22]. The outcomes of this life cycle simplifications are different tools and indexes developed by companies. These tools are used to assess products in order to categorize them in terms of sustainability.

LCA as a tool for evaluation of the product design alternatives has fallen short, the reason is that sometimes a huge amount of exercises could be locked in deep details which are confusing and time consuming [23] There have been several attempts in order to simplify LCA [24].

For example Ford developed a product sustainability index named PSI. Ford's sustainability tool has eight indicators (criteria) to simplify the life cycle of the products, and by applying it to some products reached significant improvements [22] It is interesting that Ford started with PSI tool and later on products were assessed based on the external standard of ISO 14040 which confirms the significant improvements [22].

Another example is Walmart, they have developed an index that represents the LCA assessment named "The Sustainability Consortium" (TSC). Their index consists of 15 questions which mainly focus on suppliers. It is interesting that, the same as IKEA[19], they are applying this index to particular product categories and also their aim is to integrate this tool in their core business. They also believe that by using this tool and moving toward sustainability, Walmart gains competitive advantages in terms of transparency and price [21, 25].

IKEA has made the same attempt to simplify the life cycle and assess environmental impacts in different stages of the prodocts' life cycle. There are eleven criteria considered in IKEA's sustainability assessment tool. Each criterion falls in different stages of life cycle to focus upon.

4 RESULTS

The results from 20 interviews and meetings and other observations in this case study are presented below. Additionally, the quantitative results are presented in separated sections to be used in the model development.

4.1 Sustainability assessment tool

Based on interviews, managers believe that, small improvements in environmental impact considering company's huge production scale have a significant positive influence on environment.

4.2 Goals

The company's sustainability goal is based on sales values, 70% of the sale value should be classified as More Sustainable in 2015.

More sustainable is a term used for products that get certain points or more according to the assessment tool.

As a result of such a goal, the other products which are bigger in number but have smaller sales values get ignored to some extent when it comes to sustainability improvements. This approach declares that in short term, by focusing on best selling products, maintaining the sale growth is of a higher priority in comparison with sustainability.

Interviews with marketing managers show that the best-selling products have an important role in shaping the brand image, and making those products sustainable will be a great competitive advantage in terms of sustainability.

It is clear that categorising products based on sales values represents the financial concerns of the company but there is no way to ignore the higher risks. In that regard, managers are looking for a way of finding solutions, in the product level, in order to avoid higher risks and also improve the brand image by having sustainable best-selling products. This approach corresponds to ABC classification of the products.

4.3 Financial analysis

As mentioned, by setting the goal based on the sales values, improvements are focused on best-selling products. This approach corresponds to the ABC classification of the products. ABC analysis comes in handy to understand the way of using the tool in terms of assessment. In other words, it draws the management attention to the best-selling products.

This analysis describes how the company categorises the articles and narrows them down. As illustrated in figure 2, A class products constitute 70% of the sales values, although they represent only 14% of all the products.

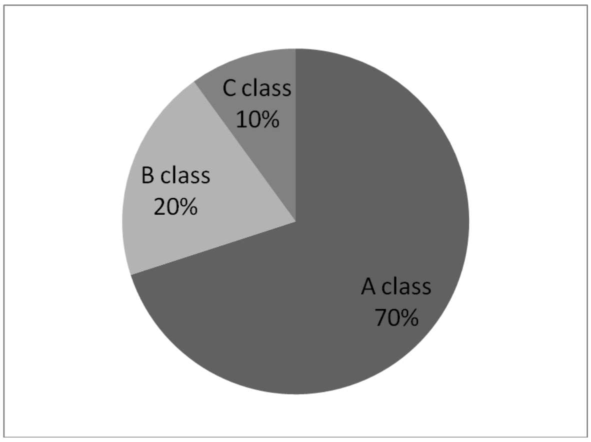


Figure 2: ABC analysis based on sales value.

ABC analysis proposes that products do not have equal values, therefore they are categorized in three groups (**A, B, and C**) in order of their importance (in this case, sales value) [26].

Like Pareto's principle, a small number of products have a large share of sales value, but there is no certain portion for each class [27]. Since this financial analysis is focusing on the current situation and future is less considered thus, there is a need for a combination of strategic and financial analysis at the same time in order to identify which products are financially and strategically important.

4.4 Sustainability assessment analysis

As illustrated in figure 3, after sustainability assessment of all products with sustainability tool, 45% are classified as more sustainable which. When we combine these results with ABC analysis, 79% of more sustainable products are A class, 14% B class and 7% C class.

The combination of sustainability assessment and ABC analysis declares more sustainable products are mostly from A class.

These results also support the results from interviews which indicate that the company is focusing on best-selling products for sustainability improvements. This analysis is used as an input for complementary interviews.

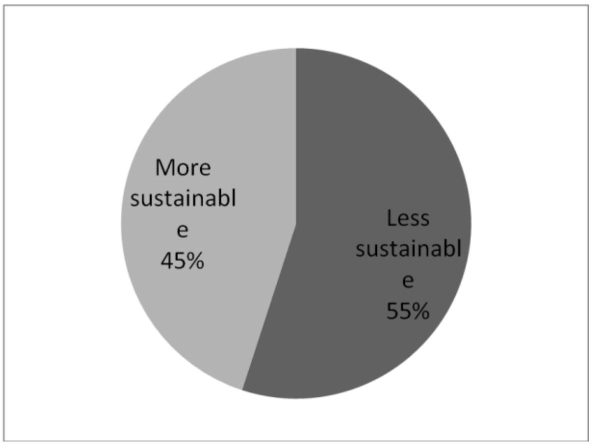


Figure 3: Sustainability status based on company's tool

5 STRATEGIC ANALYSIS AND LIFE CYCLE ANALYSIS (LCA)

The complementary interviews with focus on financial and sustainability analysis show that, there are concerns about B class and C class products that are growing and will join the A class products in future. Therefore, ignoring those products would not be wise.

Results show that, as illustrated in figure 4 some products that have high sales values (A class) will be soon declined from the market. In other words, these products are in A class but are close to the end of their life cycle (decline stage).

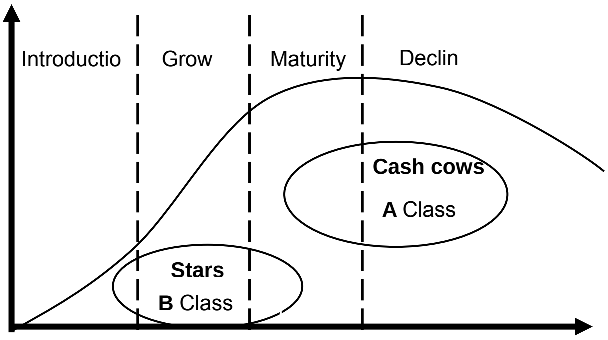


Figure 4: ABC analysis combined with life cycle analysis.

Documents show that the company uses Boston Consultant Group (BCG) matrix as a strategic tool in order to analyze its strategic position in the market compared to other competitors. The other interesting results of investigating the internal documents and complementary meetings show that the company has done the strategic analysis for products in A class.

As shown in figure 4, Considering the ABC analysis and BCG results From Boston Matrix perspective, there are products that represent cash cows in the matrix, and they are in A class, but soon they will be declined by the market and turned to the dogs. On the other hand there are products that represent stars in the matrix, and are growing in terms of market share. Additionally, findings show that there are some B class products that will be in A class in future, considering their growing market.

6 MODEL DEVELOPEMENT

Based on evidence and internal documentations, as mentioned in sustainability analysis, mostly products that have high sales values were focused on, for sustainability improvements. After conducting interviews in that regard, results showed that it was not a deliberate reaction based on a clear road map. By combining other tools and analysis, the company learns that A class products are more important in terms of sustainability. This approach is modified by other tools such as Boston matrix and lifecycle analysis.

This model shows how the company tries to identify critical products by narrowing down all products using these three dimensions to find out critical articles, which are strategically, financially and sustainability important. Combining the company's approach strategy and this model will answer the research question.

Combining all results from previous analyses delivers a three dimensional model (figure 5). Therefore, all A class articles which are strategically important and (stars in BCG matrix) and also not going to be declined from the market are company's critical articles. As mentioned, critical articles play an important role in the early stages of sustainability implementation.

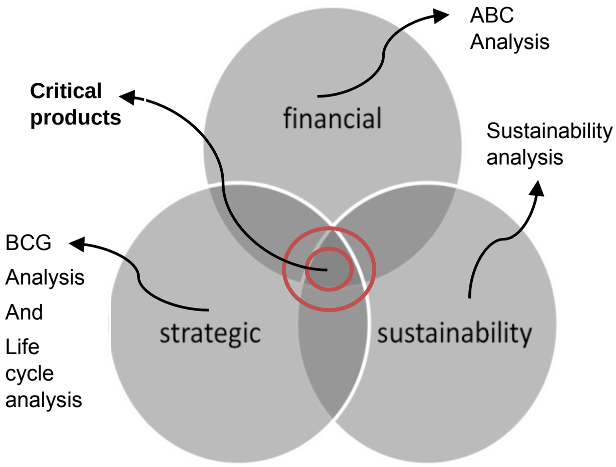


Figure 5: The developed model to find critical articles

These products, critical products, are the ones that company will focus upon for sustainability improvements. This model represents the combination of short term strategies of the company.

As can be seen in figure 5, combining financial analysis (ABC analysis in this case), strategic analysis (BSG and LCA in this case) and sustainability assessment (SPS in this case) leads to a model which is focusing on the product level.

This model describes how the company moves toward sustainability without compromising in their financial objectives in short term. Sustainability index tool as a component of short term strategy is combined with financial analysis in order to consider financial objectives. On the other hand, strategic analysis is the other component of the model which addresses the products which are currently significant and also in the future.

7 SUMMARY

As mentioned, companies try to simplify the life cycle of products and make sustainability index (tools). The internal acceptance and fast evaluating process compared to other techniques e.g. Life Cycle Assessment are the main reasons behind this simplification.

By approaching products with high sales values and low sustainability, companies have difficulties to find critical products not only based on sale but also based on sustainability, therefore they try to categorize products with combinations of tools.

It is concluded that in order to reach sustainability goals companies strategy in short term are:

- To be very tool oriented and try to simplify LCA to enhance adoption process.
- Still having a higher priority for financial aspects
- Focusing on product level for improvements to find critical articles to reach the goal

8 FUTURE RESEARCH

The following research questions are recommended for further research in this context:

manufacturers and consumers have very different perspectives on the importance of different sustainability elements [23] how can sustainability index(tool) consider both perspectives?

What is the relationship between companies' sustainability strategy and competitive advantage?

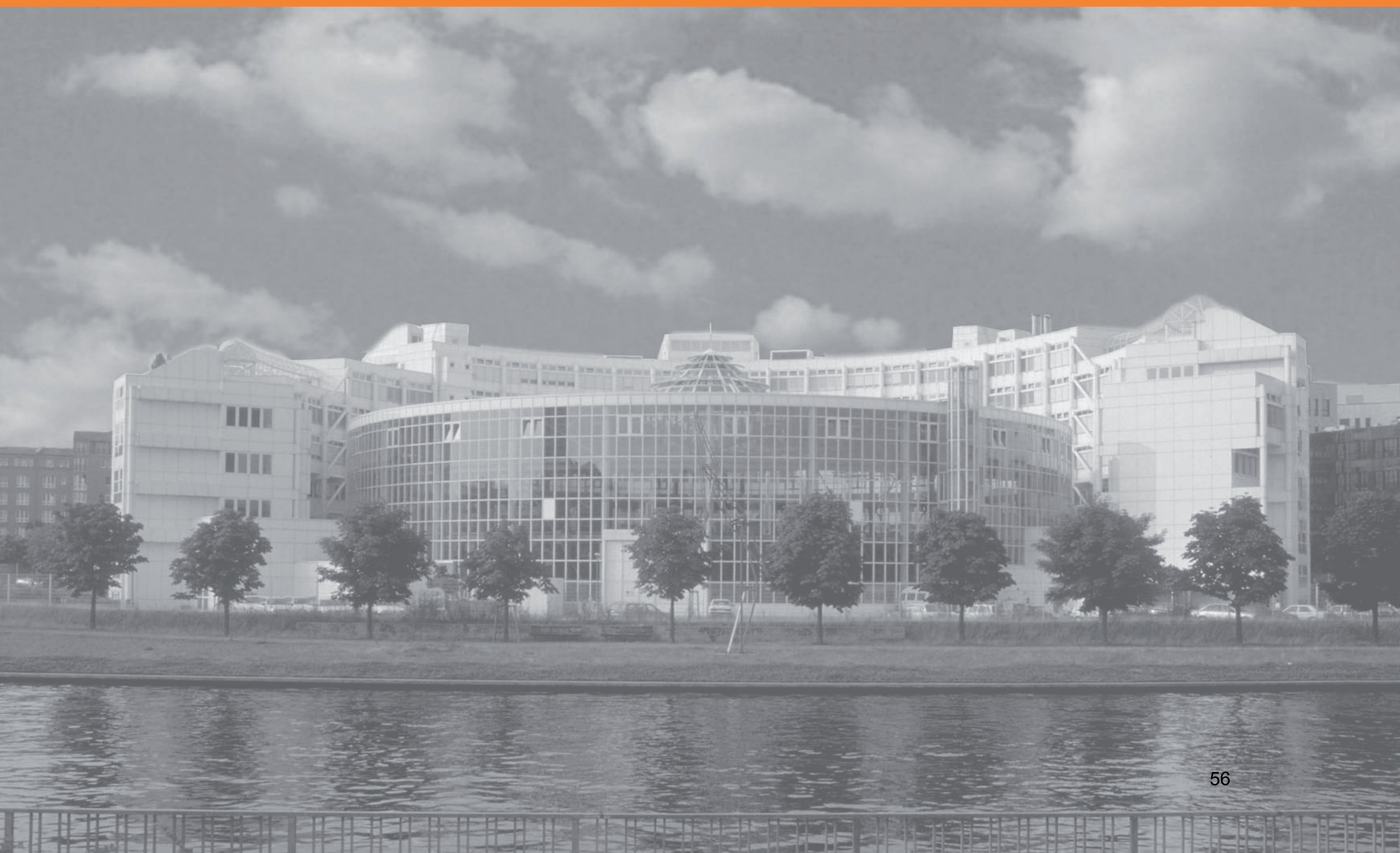
How positionening in the market regarding sustainability could be identified?

9 REFERENCES

1. Testa, F. and F. Iraldo, Shadows and lights of GSCM (Green Supply Chain Management): determinants and effects of these practices based on a multi-national study. Journal of Cleaner Production, 2010. 18(10): p. 953-962.
2. Spangenberg, J.H., A. Fuad-Luke, and K. Blincoe, Design for Sustainability (DfS): the interface of sustainable production and consumption. Journal of Cleaner Production, 2010. 18(15): p. 1485-1493.
3. Ammenberg, J. and E. Sundin, Products in environmental management systems: drivers, barriers and experiences. Journal of Cleaner Production, 2005. 13(4): p. 405-415.
4. Hallstedt, S.I., A.W. Thompson, and P. Lindahl, Key elements for implementing a strategic sustainability perspective in the product innovation process. Journal of Cleaner Production, 2013(0): p. 1-12.
5. Gaziulusoy, A.İ., C. Boyle, and R. McDowall, System innovation for sustainability: A systemic double-flow scenario method for companies. Journal of Cleaner Production, 2012.
6. Porter, M.E., 2. Green and Competitive: Ending the Stalemate. The Dynamics of the eco-efficient

economy: environmental regulation and competitive advantage, 2000: p. 33.
7. Nidumolu, R., C.K. Prahalad, and M. Rangaswami, Why sustainability is now the key driver of innovation. Harvard business review, 2009. 87(9): p. 56-64.
8. Wilkinson, A., M. Hill, and P. Gollan, The sustainability debate. International Journal of Operations & Production Management, 2001. 21(12): p. 1492-1502.
9. Hallstedt, S., et al., An approach to assessing sustainability integration in strategic decision systems for product development. Journal of Cleaner Production, 2010. 18(8): p. 703-712.
10. Willard, B., The next sustainability wave: Building boardroom buy-in. 2005: New Society Pub.
11. Dangelico, R.M. and D. Pujari, Mainstreaming green product innovation: why and how companies integrate environmental sustainability. Journal of Business Ethics, 2010. 95(3): p. 471-486.
12. Nedergaard, P. and R. Töreman, The Sustainability Product Scorecard at IKEA:-framework and range analysis. 2012, KTH.
13. Boks, C., The soft side of ecodesign. Journal of Cleaner Production, 2006. 14(15): p. 1346-1356.
14. Hallstedt, S., A foundation for sustainable product development. 2008: Department of Mechanical Engineering, Blekinge Institute of Technology.
15. Deutz, P., G. Neighbour, and M. McGuire, Integrating sustainable waste management into product design: sustainability as a functional requirement. Sustainable Development, 2010. 18(4): p. 229-239.
16. Johansson, G., Success factors for integration of ecodesign in product development: a review of state of the art. Environmental Management and Health, 2002. 13(1): p. 98-107.
17. Jørgensen, T.H., A. Remmen, and M.D. Mellado, Integrated management systems–three different levels of integration. Journal of Cleaner Production, 2006. 14(8): p. 713-722.
18. Robèrt, K.-H., et al., Strategic sustainable development—selection, design and synergies of applied tools. Journal of Cleaner Production, 2002. 10(3): p. 197-214.
19. Komassi, E., The sustainability product scorecard at IKEA – Strategy development Analysis, in Swedish school of textile. 2013, Boras University.
20. De Silva, N., et al., A new comprehensive methodology for the evaluation of product sustainability at the design and development stage of consumer electronic products. International Journal of Sustainable Manufacturing, 2009. 1(3): p. 251-264.
21. Walmart, b. Developing a sustainable standard for products 2012 [cited 2013 15 May]; Available from: http://corporate.walmart.com/global-responsibility/environment-sustainability/sustainability-index.
22. Schmidt, W.-P. and A. Taylor. Ford of Europe's product sustainability index. in Proceedings of 13th CIRP International Conference on Life Cycle Engineering. Leuven May 31st–June 2nd. 2006.
23. Jayal, A., et al., Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology, 2010. 2(3): p. 144-152.
24. Kaebemick, H., M. Sun, and S. Kara, Simplified lifecycle assessment for the early design stages of industrial products. CIRP Annals-Manufacturing Technology, 2003. 52(1): p. 25-28.
25. Walmart. Welcome to the Walmart Sustainability Index Supplier Resource Center. 2013 [cited 2013 15 May]; Available from: http://customers.icix.com/walmart/sustainability-index/.
26. Lun, Y.V., K.-H. Lai, and T.E. Cheng, Shipping and logistics management. 2010: Springer.
27. Lysons, K. and B. Farrington, Purchasing and supply chain management. 2006: Ft Press.

Session 2
Value Creation



2.1 A conceptual sustainable domain value stream mapping framework for manufacturing

Noordin Mohd Yusof [1], Muhamad Zameri Mat Saman[1], Nithia Kumar Kasava[1]

[1]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia

Abstract

Adoption of lean manufacturing generally involves waste reduction and its adoption has been successful in improving companies. With increasing awareness on the need for sustainable development, works have been done on sustainability assessment of product design and manufacturing processes. The sustainable manufacturing, 6R method can be adopted to improve the existing design and manufacturing sustainability scores. A conceptual hybrid framework integrating lean manufacturing with sustainable manufacturing theories has been developed thus enabling the benefits from both techniques to be gained. Specifically, the lean manufacturing, value stream mapping tool is integrated with the sustainable manufacturing, 6R method to assist in solving manufacturing problems at process and or plant level sustainably. An indicator, providing the sustainability scores on value adding and non value adding elements at present and future state, has been proposed as part of the framework.

Keywords: Lean Manufacturing, Value Stream Mapping and Sustainable Manufacturing.

1 INTRODUCTION

Manufacturing has become the backbone of a nation's social and economic growth and an enabler for improved standard of living [1]. Sustainable development is the fundamental element in sustainable manufacturing. Sustainable development is supported by three pillars, viz. economic, environment and social. The United Nations' Brundtland Commission (1987) defines sustainable development as:

"*Development that meets the needs of the present without compromising the ability of future generation to meet their own needs*".

The Brundtland definition is fundamentally in line with sustainable manufacturing. The natural resources which the earth provides in the form of raw materials used for manufacturing products are finite and non renewable. Depletion of these raw materials through unsustainable practices will cause hardship to the manufacturing community. The manufacturing sector despite its positive contribution to development produces industrial wastes which pollute the environment. Thus, sustainable development concept has been seen to provide a solution for environmental impact. Sustainability improves societal standard and enhances the availability of resources and ecosystem for current and future generation needs [2]. The motivation for the development of this sustainable domain value stream (SdVSM) framework is to overcome the critics of lean manufacturing. The critics lamented that lean manufacturing place less emphasis on human factor or societal lagging and it is shop floor based [3]. Hence by integrating the sustainable triple bottom line pillars, lean will cover all aspects viz. societal, economical and environment waste.

2 SUSTAINABLE MANUFACTURING

Manufacturing invariably involves a business which involves products that have been produced based on some market demand. In any business there is a need to be competitive in order to gain more market share. By adopting sustainability, an organization will gain competitive advantage which enhances its survival [4]. By employing sustainability, environmental related issues will be prevented thereby reducing the product cost [5]. Sustainability is a cross over between the environment and product design [6]. Sustainable manufacturing paradigm introduces environment concerns in product design stage [7]. An environment conscious product improves product quality and market share [8]. Figure 1 shows the evolution of sustainable manufacturing over time. The stakeholders' value and involvement increases with the evolution and innovation [9]. Sustainable manufacturing at the system level is viewed as the multiple life cycle of the entire supply chain. The life cycle stages are categorized as pre manufacture, manufacture, use and post use phase [10]. On the other hand, [11] has broken the product life cycle into five stages: Pre manufacture, manufacture, product delivery, use and recycle. There was a need for the evolution from 3R to 6R methodology at product level so as to enable the migration of the product life cycle from an open loop to close loop and with multiple life cycle [11]. At the process level in order to achieve sustainable manufacturing, the technological improvements and process planning are the key drivers for reducing resource consumption, energy consumed, waste and environmental impacts [12]. Lean tools are used to solve manufacturing problems in a company [13]. Fusing lean manufacturing technique and sustainable development will improve quality, reduced cost, reduced delivery lead time and improve customer satisfaction [14].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

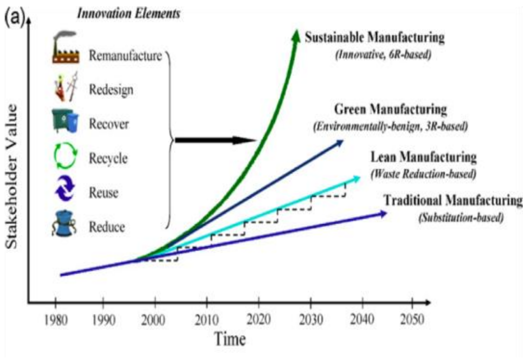


Figure 1: Evolution of sustainable manufacturing [9]

In lean manufacturing, a continuous identification and elimination of waste in the process is the primary philosophy. Eiji Toyoda and Taiichi Ohno developed this lean approach in 1950s and 1960s at Toyota [15]. A waste in a process is defined as other than the minimum amount or quantity required for equipment, parts, materials and working hours in a production or process [16]. Taiichi Ohno had defined seven common forms of waste. This waste purely contributes to the cost but no value. Polarization of resources was introduced as an eighth waste. A conceptual resource mapping framework was applied for polarization resource waste. The polarization meant here was by aligning the resources to maximize value adding contribution [17]. List of Ohno waste [18] and [17], as the eighth waste; production of goods that not yet ordered, waiting, rectification mistakes, excess movement, transport, excess stock and polarization resources.

Value in products is defined as the premium that customer is willing to pay for [15]. In any value stream of manufacturing, an approximate 5% is value adding activities, 35% are non value adding but necessary and 60% non value adding at all [16]. Reference [19] classified the values in internal manufacturing as value adding (VA), necessary non value adding (NNVA) and non value adding (NVA).

The value stream mapping has seven types of tool. Table 1 shows the seven types of value stream mapping tools and its usefulness [20]. Value stream mapping is a lean tool which involves a paper and pencil tool with fixed icons that is a cheap and easy to use [21].

A value stream mapping provides a visualization of the material and information flow in the company and or even supplies chain, thus facilitating decision making to improve the value stream [22]. Traditional value stream mapping improvements are accomplished by employing lean tools. Sustainable indicators comprised of triple bottom line where economical, environmental and societal impacts measured. Indicator is "*a measurement or aggregation of measures from which conclusions on the phenomenon of interest can be inferred*" [23]. The Sustainable Measures Group has established the criteria for the indicator [24]. The criteria are measurable, relevant, reliable, accessible, timely manner and long time oriented. Fulfilling the indicator criteria will ensure accurate data, appropriate decision making and ease representation in qualitative or quantitative. Table 2 provides a summary of literature on various sustainable indicators.

3 SUSTAINABLE DOMAIN VALUE STREAM MAPPING CONCEPTUAL FRAMEWORK

Sustainable Domain Value Stream Mapping (SdVSM) conceptual framework is the integration between lean manufacturing and value stream mapping tool [20] with innovative 6R sustainable manufacturing methodology [25]. Part of the framework consists of visualizing the sustainable indicators based on sustainable scoring method. The framework has two dimensions, first is the lean manufacturing dimension. Here a modified value stream mapping was used to identify the waste in the manufacturing system. In value stream mapping there are seven types of tools and in this model the process activity mapping will the tool. Process activity mapping tool is the simplest tool used to map any process into activities. This tool is easily applied to process, plant or product level.

The second dimension is the sustainable manufacturing element. In this element, 6R methods have been used as tool; reduce, reuse, recycle, recover, redesign and remanufacture.

Table 1: Seven value stream mapping tool with usefulness [20]

Seven Stream Mapping Tools	High Correlation and Usefulness in Waste (Ohno)
Process Activity Mapping	Waiting, Transport, Inappropriate processing and unnecessary motion
Supply Chain Response Matrix	Waiting and unnecessary inventory
Production Variety Funnel	Inappropriate processing and unnecessary inventory
Quality Filter Mapping	Defects
Demand Amplification Mapping	Unnecessary inventory and overall structure
Decision Point Analysis	Overproduction
Physical Structure (a) volume, (b) value	Overall structure

Table 2: Literature on various sustainable indicators [23]

No.	Sustainable Indicators	Summary
1	Global Report Initiative (GRI)	Organization level reporting that covers sustainable development three dimension pillars.
2	Dow Jones Sustainability Indexes (DJSI)	Only top ten percent of companies that is listed in Dow Jones Global Total Stock Market Index. It is a financial and sustainable assessment for investment.
3	2005 Environmental Sustainability Indicator (ESI)	A country or region level environmental evaluation developed by Yale University.
4	Environment Performance Index (EPfI)	Measures the environment stress at country level and complement the ESI. Developed by Yale University.
5	United Nations Indicators of Sustainable Development (UN CSD)	Evaluate the degree of sustainability in a country or regional level.
6	Organization for Economic Cooperation and Development (OECD) core environmental indicator (ECI)	Monitors sustainability indicators of a country.
7	Ford Product Sustainability Index (Ford PSI)	Specialized to automobile manufacturing and service.
8	International Organization for Standardization (ISO) Environmental Performance Evaluation (EPE) standard (ISO 14031)	Specifically covers environmental indicators.
9	Environmental Pressure Indication for European Union (EPrI)	Assessing human activities that given environmental impact.
10	Japan National Institute of Science and Technology (NISTEP)	Indicators that counts the sustainable technological advancement.
11	European Environmental Agency Core Set Indicators (EEA-CSI)	Environment improvement indicators for European Countries.

Reduce refers to first three stages of product life cycles and attempts are made to reduce the use of resources, materials and energy at pre-manufacturing and manufacturing and reduce the waste generated at the use stage [25]. The reuse method is accomplished by reusing the material and energy of a product or component from the first product life cycle to the next life cycle. This method minimizes the usage of raw material for the same product. Recycle is a process of transformation of product at the end of life cycle to a new product. This saves the product to be sent to landfill. The recover is a method of recollecting the used or end of life product and then to be sent for disassemble and cleaned for the next process or life cycle. Redesign where products are simplified at design stage for sustainability for example the concept of design for environment (DfEnv) or design for sustainability (DfS). The sixth R is remanufacturing where the process involves re-processing used product to its original state of design. This is accomplished by reusing the sub parts and parts without loss of functionality of the entire product.

The authors have developed a conceptual framework; see Figure 3 for the SdVSM framework matrix. The entire conceptual framework has tangible and intangible components. The intangible component is the ideology of the framework structure whereby the user will be guided by a series of flow chart type instructions for implementation. The tangible part of the framework consists of a visual sustainability score indicator. This indicator is visualization schematic that gathers sustainability parameters and generates sustainable scores for value adding (VA) and non value adding (NVA). The ideology and visual schematic are driven by SMMIAI methodology for sustainable manufacturing. SMMIAI consists of seven steps of action. Each step has its own define function that requires different

Table 3: SdVSM Conceptual Framework Matrix.

SMMIAI METHODOLOGY	SUSTAINABILITY PILLARS		
	Social	Environmental	Economical
Select	Select study domain at plant level or department level.		
Map	Map the activities using Sustainable domain value stream mapping tool (SdVSM). At this stage VA and NVA activities will be identified.		
Measure	Measure the associated parameter of activities and compute sustainability scores based on SMIR 2013. Sustainable score will quantify the value adding and non value adding activities.		
Improve	Improve problem area viz. activities with low sustainable scores and as well as NVA activities.		
Analyze	Analyze the before and after sustainable scores across the activities after 6 R improvement.		
Indicate	Indicate graphically the before and after improvement sustainability score for value adding and non value adding activities using SdVSM		

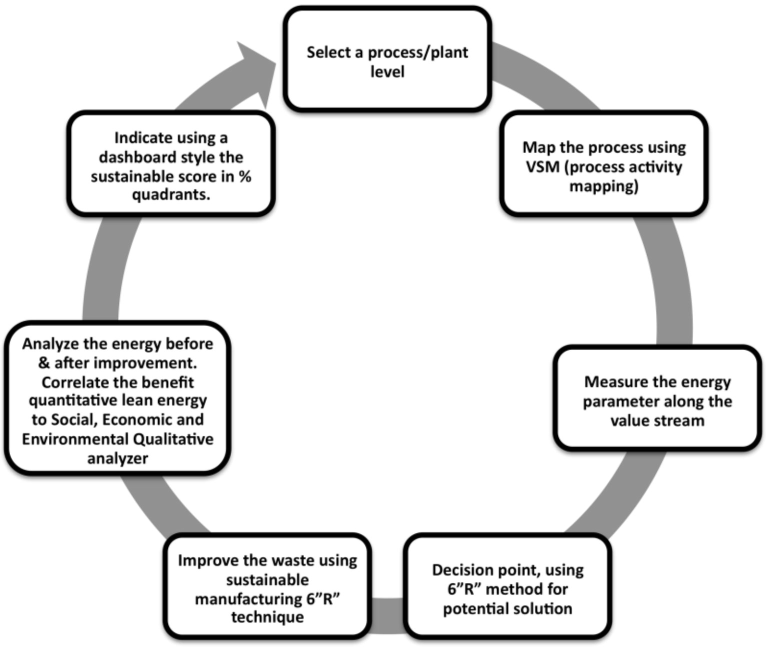


Figure 4: SMMIAI workflow for Sustainable Domain Value Stream Mapping

methods or skills. Figure 4 provides an illustration of the workflow in a simplified manner. In conventional value stream framework, time will be the domain of performance measurement. The lean component will be the value adding and non value adding activities embedded in the value stream [19]. In the conceptual SdVSM framework, time is no longer a domain for measure in the value stream. The sustainable pillars will be the domains. Each activity in the value stream will be measured in sustainable score. For example electrical energy consumption of a process will be measured as the ratio of electrical energy consumed for value adding over electrical energy consumed non value adding. This ratio will be average out from sustainability pillar component.

This framework will evaluate and indicate the sustainable scores on the value adding and non value adding activities in the manufacturing and or in the supply chain. The non value adding activities are considered as waste in the system. Hence the waste is now broken down using triple bottom line sustainable categories, which is societal, impact, economical impact and environmental impact [26]. Equation 1 shows the summation of sustainability score for value adding (Sva) activities and Equation 2 shows the sum of sustainability score for non value adding (Snva) activities. This non value adding activities will be the target for improvement using the 6 R innovative methodologies. In this framework since it inherit the value stream mapping characteristic thus present state and future state can be developed. In this framework the authors used the process activity mapping as the value stream mapping tool. Figure 5 shows the SdVSM sustainable score indicator by activities using process activity mapping.

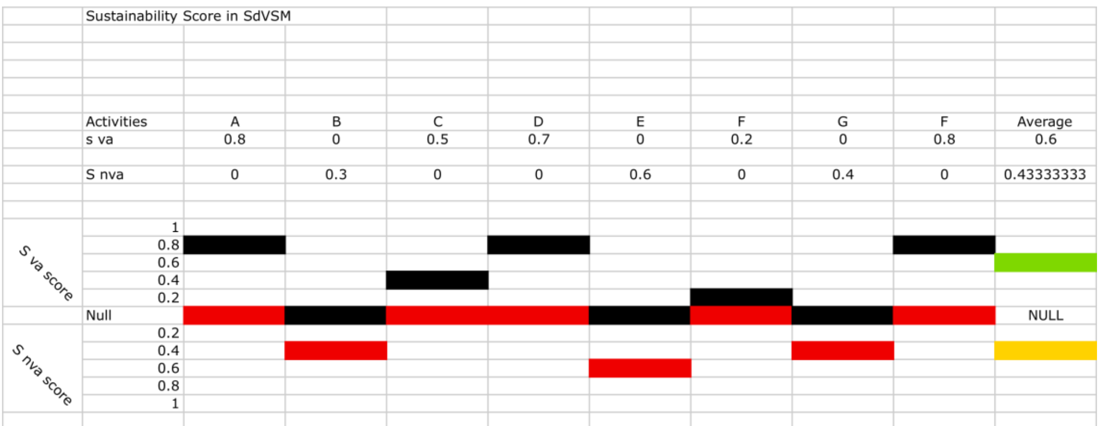


Figure 5: SdVSM framework Indicator Phase for Visualization (fictitious values given).

$$\sum_{i=1}^{n} Sva = \sum_{i=1}^{n} (social + economical + environmental) \forall \in VA \quad (1)$$

$$\sum_{j=1}^{m} Snva = \sum_{j=1}^{m} (social + economical + environmental) \forall \in NVA \quad (2)$$

Hence low sustainable scores are the potential areas to be improved using the 6R innovative improvement agent. In this framework, 6R method used on process improvement where traditionally used on product and product life cycle. The sustainable metrics are referred to Sustainable Manufacturing Indicators Repository (SMIR 2013) from National Institute of Standards and Technology (NIST) United States of America. SMIR 2011 contains 212 total sustainable indicators [23]. See Table 3 for NIST sustainable manufacturing indicator categorization and sub categories. Table 3 will be general guide for sustainability metrics on the mapped value stream.
In order to determine the level of achievement of the framework a benchmarking will be used for improvement evaluation. Methods of obtaining benchmark values are from the past performance data from the company, standards and set goals for amount of reduction within given time frame [23]. After improvement the sustainable score will be re calculated to indicate before and after scores.

Table 4: NIST Sustainable manufacturing indicator repository [23]

SUSTAINABILITY ELEMENTS	SUSTAINABILITY PARAMETERS	REMARKS
Environmental	Emission	Solid waste emission, air emission, waste energy emission
	Pollution	Hazard substance, Green House Gases, Ozone depleting gases.
	Resource Consumption	Water used Material used (Overall, virgin, reuse, remanufactured, recycled and other material) Energy consumption (Total energy consumed, Renewable energy consumed, Non renewable energy consumed) Land used
	Natural habitat conservation	Bio diversity, habitat management and conservation.
Economical	Costs	Manufacturing cost, material acquisition cost, production cost, product transfer to customer cost, end of life product handling cost.
	Profit	Profit earned by the organization
	Investment	Eco friendly investment
Social	Employee	Health and safety Professional development Employee satisfaction
	Customer	Health and safety of the product at use phase Customer satisfaction with the product Customer rights
	Community	Product responsibility (Justice, Community development program, Fairness, Equity, Human rights, Corruption) Development (Public service policy) Population

4 CONCLUSION

This conceptual framework has advantages over lean manufacturing because lean focuses on operational metrics and by integrating with the triple bottom line sustainability pillars the human factor, costing and environmental issues were taken into account. The second differences from the traditional value stream mapping where takt time, cycle time and waiting were the domain. However in this conceptual framework the triple bottom line of economical, environmental and societal will be the domain across the value stream. A radical improvement tool is used which is the innovative 6 R methodology, where by the 6 R method which was commonly applied at the product level but here it is used for process level improvement. In contrast to the conventional method of improvement in value stream mapping is through the use of lean tools. The framework indicators are representation of sustainability scores of value adding and non value adding activities. Thus decision and improvement affects directly the sustainability level in the chain of activities. This paper introduces the sustainable domain value stream mapping (SdVSM) framework as a conceptual framework and will be tested in a case study to validate it as an operational framework. There is high industrial potential of this framework is due to its simplicity and ability to be applied on the process level whether it is an open loop and close loop manufacturing process activity chains.

5 ACKNOWLEDGEMENT

The authors wish to thank the Ministry of Higher Education (MOHE), Universiti Teknologi Malaysia (UTM) and Research Management Center, UTM for the financial support to this work through the Long Term Research Grant Scheme (LRGS) funding number 4L804

6 REFERENCES

[1] Jovane F. Yoshikawa H. Alting L. Boer G. R. Westkamper E. Williams D. Tseng M. Selinger G. Paci A. M. 2008, The Incoming Global Technological and Industrial Revolution Towards Competitive Sustainable Manufacturing, CIRP Annals Manufacturing Technology, 57, 641-659.

[2] Selinger. G. 2007, Sustainability in Manufacturing, Recovery of Resources in Product and Material Cycle, New York, Springer.

[3] Hines. P. Rich. N. 1997, The Seven Value Stream Mapping Tools, International Journal of Operations & Production Management, Vol. 17 (1) pp. 46 – 64.

[4] Bevilacqua M. Ciarapica F. E. Giacchetta, G. 2007, Development of a Sustainable Product Lifecycle in Manufacturing Firms: A Case Study, International Journal of Production Research, 45 (18–19), 4073–4098.

[5] Senthilkumaran D. Ong S. K. Tan B. H. Nee A. Y. C. 2001, Environmental Life Cycle Cost Analysis of Products, Environmental Management and Health, 12 (3), 260–276.

[6] Rusinko C. A. 2007, Green Manufacturing: An Evaluation Of Environmentally Sustainable Manufacturing Practices and Their Impact on Competitive Outcomes, IEEE Transactions on Engineering Management, 54 (3), 445–454.

[7] Conteras A. M. Rosa E. Prez M. Langenhove H. V. Dewulf J. 2009, Comparative Life Cycle Assessment of Four Alternatives for Using By-Products of Cane Sugar Production, Journal of Cleaner Production, 17, 772–779.

[8] Soriano V. J. Kaebernick H. 2000. An Approach to Simplified Environmental Assessment By Classification of Products. In: Proceedings of the Seventh CIRP International Seminar on Life Cycle Engineering; pp. 163–169.

[9] Jayal.A.D. Bodurdeen. F. Dillon. Jr. O.W. Jawahir. I.S. 2010, Sustainable Manufacturing: Modeling and Optimization Challenges at the Product, Process and System Level, CIRP Journal of Manufacturing Science and Technology, 2, 144-152.

[10] Badurdeen. F. Goldsby. T.J. Iyengar. D. Metta. H. Gupta. S. Jawahir. I.S. 2010, Extending Total Life Cycle Thinking to Sustainable Supply Chain, International Journal of Product Life Cycle Management, 4(1/2/3), 49-67.

[11] Graedel. T.E. 1998, Streamline Life Cycle Assessment, New Jersey, Prentice-Hall.

[12] Jawahir. I.S. Dillon. Jr. O.W. 2007, Sustainable Manufacturing Process: New Challenges for Developing Predictive Models and Optimization Techniques, Proceeding of the 1st International Conference on Sustainable Manufacturing, Montreal, Canada.

[13] Herron. C. Braiden. P. M. 2006, A Methodology For Developing Sustainable Quantifiable Productivity Improvement in Manufacturing Companies, International Journal of Production Economics, 104, 143-153.

[14] Nitin. U. Deshmukh. S. G. Suresh. G. 2010, Lean Manufacturing for Sustainable Development. Global Business and Management Research: An International Journal, 2 (1), 125-137.

[15] Womack. J.P. Jones. D.J. Ross. D. 1990, The Machine that Changed the World, New York, Rawson Associates.

[16] Suzuki. K. 1978, The New Manufacturing Challenges: Techniques for Continuous Improvement, New York, Free Press.

[17] Paul M. Gibbons, Colin Kennedy, Stuart C. Burgess, Patrick Godfrey, 2012, The Development of a Lean Resource Mapping Framework: Introducing an 8th Waste, International Journal of Lean Six Sigma, Vol. 3 (1) pp. 4 – 27.

[18] Shingo. S. 1989, A Study of the Toyota Production System from an Industrial Engineering Viewpoint, Cambridge, MA. Productivity Press.

[19] Monden. Y. 1993, Toyota Production System: An Integrated Approach to Just-in-Time, 2nd ed., Industrial Engineering and Management Press, Norcross, GA.

[20] Hines. P. Holweg. M. and Rich. N. 2004, Learning to Evolve: A Review of Contemporary Lean Thinking, International Journal of Operations & Production Management, Vol. 24(10). pp. 994-1011.

[21] Abdulmalek. F.A. and Rajgopal. J. 2007, Analyzing the Benefits of Lean Manufacturing and Value Stream Mapping Simulation: A Process Sector Study, International Journal Production Economics, 107 (1). 223-236.

[22] McDonald. T. Van Aken. E. M. Rentes A. F. 2002, Utilizing Simulation to Enhance Value Stream Mapping: A Manufacturing Case Application, International Journal of Logistics: Research and Applications 5 (2), 213–232.

[23] Joung C. B. Carrell J. Sarkar P. Feng S. C. 2012, Categorization of Indicators for Sustainable Manufacturing, Ecological Indicators, 24. 148-157.

[24] Sustainable Measures, 2009, <<accessed via http://www.sustainablemeasures.com. >> <<accessed on 30 November 2012 >>.

[25] Joshi. K. Venkatachalam. A. Jawahir. I.S. 2006, A New Methodology for Transforming 3R Concept for Improved Product Sustainability In. Proceeding of the IV Global Conference on Sustainable Product Development and Life Cycle Engineering, Sao Carlos, Brazil.

[26] Elkington. J. 1998, Cannibals with Forks: The Triple Bottom Line of 21st Century Business, Gabriola Island, New Society Publisher.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany
CIRP

2.2 Sustainable value creation through innovative product design

K. Daniel Seevers[1], Fazleena Badurdeen[2], I. S. Jawahir[2]
[1]Lexmark International Incorporated, USA
[2]Institute for Sustainable Manufacturing, University of Kentucky, USA

Abstract
In the field of product development, many organizations struggle to create a value proposition that can overcome the headwinds of technology change, regulatory requirements, and intense competition, in an effort to satisfy the long-term goals of sustainability. Today, organizations are realizing that they have lost portfolio value due to poor reliability, early product retirement, and abandoned design platforms. Beyond Lean and Green Manufacturing, shareholder value can be enhanced and optimized by taking on a broader perspective, and integrating sustainability innovation elements into product designs.

This paper presents a framework for achieving the goal of mutual value creation, and identifies the drivers of product design that are used to ultimately create what is termed - The Sustainable Products Value Proposition. Focus is placed on a balanced approach towards the integration of total cost of ownership, social and environmental improvements, and an expanded definition of product life drivers.

Keywords: Sustainability, Sustainable Value Proposition, Product Design, Product Half Life

1 INTRODUCTION

Technology advancements and new innovations continue to fuel the fast pace of new product introductions available to consumers around the world. In 1965, Gorden E. Moore predicted the number of transistors on integrated circuits would double every two years [1]. Today his relatively accurate prediction, better known as Moore's Law, serves as a symbolic backdrop for the exponential growth of consumer electronics as well as design evolutions in the majority of industrial categories. With each new product introduction, consumers are presented with such possibilities as increased productivity, improved communications and information flow, and even improved quality of life [2] [3]. But, with the ever increasing hunger for products that consume the world natural resources, questions arise of how to measure the benefits new technology brings to humankind vs. the potential wake of waste streams left in its path. The challenging concept is balancing the **e-gain** - benefits from new technology vs. the **e-waste** - of abandoned products. (see Figure 1)

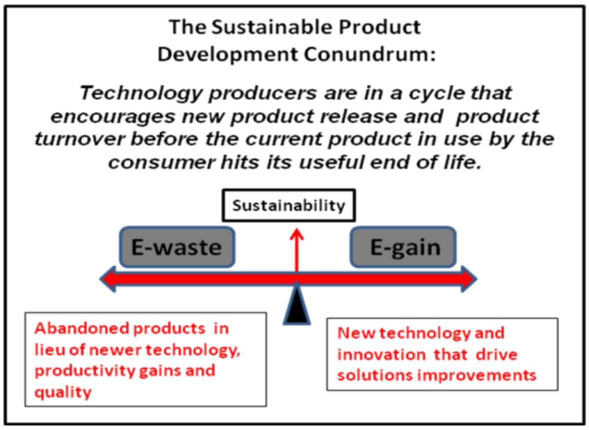


Figure 1: The balance between e-gain and e-waste.

To illustrate the affects of early product withdrawal, the study of the half-life of product families is introduced -- see Figure 2. The half-life is defined as the point where half of the products sold within a product platform (model family) are no longer used in the market. The graph presents models of relative half-life estimates for various types of material goods.

The chart exposes the challenges producers of consumer electronics and other high technology industries face where it is possible that the half-life of a product family is shorter than the time it took to develop the product. When product half-life data is superimposed on product financial models, even greater insight on the potential risk of early product abandonment is possible. The details behind these dynamics can aid in research towards the development of sustainable products and processes.

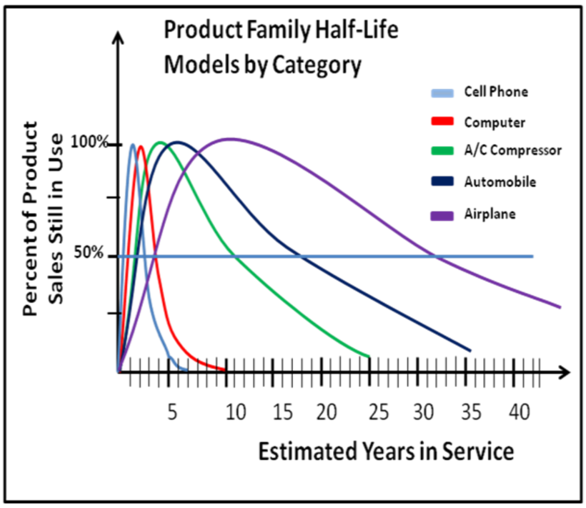


Figure 2: Relative product half-life curves of selected product families.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

As a matter of strategy, engineers do not set out to design new products for the sake of creating waste, in fact producers face a new product development conundrum: *Technology producers are in a cycle that encourages new product release and product turnover, before the current product in use by the consumer hits its useful end of life.* In order to draw attention to the research necessary to help improve the development of sustainable products and processes, especially from a waste stream perspective, the perceived value should be well-understood and addressed.

Recently, there has been an increase in research centered on sustainable value [4]. In a paper by Ueda et. al. [5], value creation models were presented based on emergent systems and co-created decision making. This paper studied the relationships between natural, social, and artifactual systems. In related research, Tolio et. al. [6] focused on the complexity of economic, socio-political and technological dynamics. We focus our attention on the cost drivers of a sustainable value proposition used to develop products and drive innovative solutions --- see Figure 3.

With the help of NGO's, industry representatives, and government employees, influence on the long-term effects of sustainable products have increased in some industries. The potential for even greater value creation is not only possible, but also necessary, for improving sustainability in products from generation

to generation. At the heart of this proposition is the creation of mutual value between consumers and producers, as well as society and the environment.

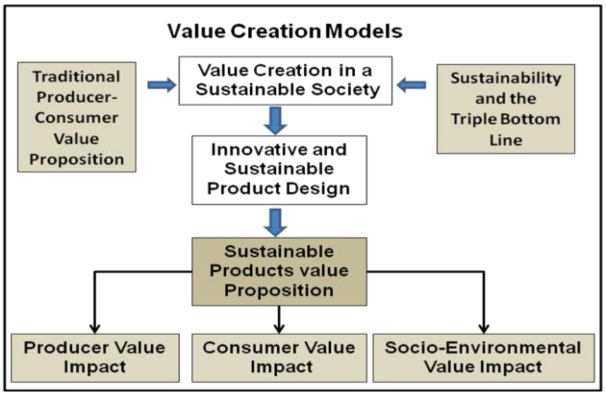


Figure 3 : Sustainable value creation framework for products.

In this paper, we identify the high impact drivers for each pillar of the Sustainable Value Proposition. In doing so, the design engineer will have a set of metrics that will aid in the optimization of value creation in generation-to-generation product development.

2 BACKGROUND

According to an ASME survey focused on the trends related to sustainability in product development, the overriding reason why corporations integrate sustainability factors into their designs is due to government regulations [7] [8]. This report surveyed engineers for reasons why they would consider sustainability in their product designs. In additon to regulations, rising energy costs and client demand rounded out the top three motivating factors to develop more sustianable products. Only 16 percent of respondents included the potential for improved return on investment. In a similar survey conducted by the MIT Sloan Mangement Review and the Boston Consulting Group, which focused on integrating sustainability into the developmnet process, 45% of respondents report that they expected higher operational cost to take away from profits. Thirty three percent cited the administrative costs of sustainability programs would create additional losses [9]. The results of the surveys show that in order to keep the attention of the design engineer when developing next generation products, or grab the attention of the consumer in the purchase of their next solution, sustainable value must be reviewed from their individual as well as mutual perspectives.

The triple bottom line (TBL) of sustainable development focuses on meeting the needs of the present without compromising the ability of future generations to meet their own needs [10]. In the center of this focus is the concept of the three pillars of sustainability, which requires the reconciliation of environmental, social and economic demands within the context of development. While the engineering community is familiar with the TBL, many struggle to project the concepts onto their own work. In order to put focus on sustainable value, we look to identify the overlapping benefits between the producer, consumers and the socio-environment. An additional set of pillars is referred to as the Sustainable Value Drivers (Figure 4).

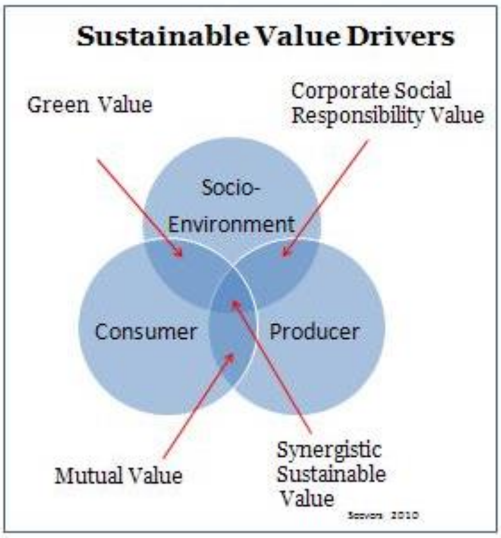


Figure 4: Sustainable value drivers.

New industries in **green marketing** have been created for consumers who seek out environmentally conscious products. Producers are motivated to show their social and environmental value through **corporate social responsibility reporting** (CSR). Consumers and producers often work together to create **mutual value** focused on solutions that reduce workflow and resource consumption. Yet, many engineers lack the tools or foresight to break the new product design process down into the driving metrics that would seek new value creation for the consumer, producer and the socio-environment at the same time. In order to indentify the driving aspects of the proposal, long-term value must be examined from each perspective.

Producer Value: In order for producers to be profitable, designers strive to develop products that meet customer needs at acceptable production and delivery cost – thereby creating a mutual value proposition. Product use and life are the key deliverables.

Consumer Value: Potential Customers seek out innovative solutions that meet their needs. In doing so, consumers weigh these potential solutions against the total cost of purchasing and owning the product.

Socio-Environmental Value: From a sustainability perspective, new products or solutions that improve the health and well being of society without affecting the need of future generations to meet their needs.

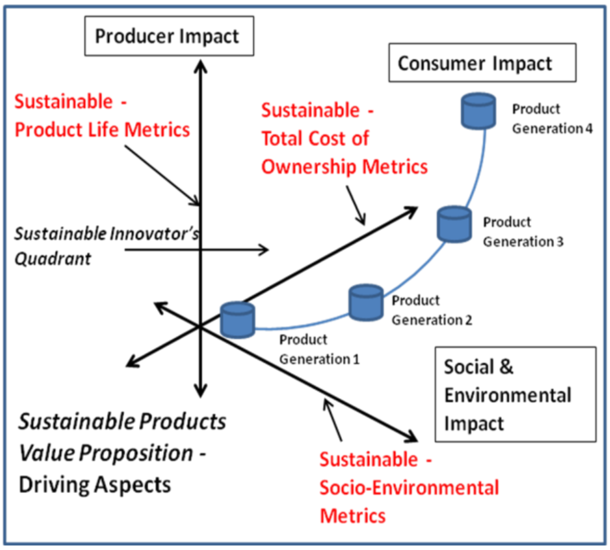


Figure 5: Sustainable products value proposition drivers.

These concepts are not difficult when studied on an individual basis, but creating solutions that optimize the three key pillars of design value is difficult. In fact, as the world becomes more competitive, the headwinds that development engineers face continues to complicate their ability to achieve the desired goal of sustainable development. For example, manufacturing losses, abandoned design platforms, and early product retirement are all examples of waste stream that create losses to producers, consumers, as well as to society and the environment. Certainly, research in topics focused on lean manufacturing and green marketing can help improve the bottom line. But, in order to have the greatest impact on the long-term development of products and processes, focus should be on developing a Sustainable Products Value Proposition that integrates sustainability innovation elements into the product design value proposition. These elements carry the design concepts beyond the traditional 3R's of reduce, reuse and recycle, to include recovery, redesign and remanufacture [11].

3 PRODUCER, CONSUMER AND SOCIO-ENVIRONMENTAL IMPACTS

One difficulty in developing a common set of aspects in the design of sustainable products and processes is the need to integrate a wide array of drivers into one common analytical metric set. In the process of identifying the driving aspects of the sustainable products value proposition, categories that have the highest impact from a value perspective are identified. In this process, value is viewed as the potential for new utility relative to its cost. In order to have the highest impact on the long-term goals of sustainability, generation-to-generation product designs should seek to improve each pillar of the driving aspects at the same time. (Figure 5) If design improvements are achieved in all three impact areas, the producers are developing products in the Sustainable Innovator's Quadrant.

A common paradigm of development engineers is the assumption that the bill of materials must increase in order to create solutions that accomplish goals such as extending life, meeting regulations, or lowering the cost for the customer to operate. In order to break down this paradigm, detailed drivers for each aspect are identified to provide a broader perspective to the key stakeholder of the value proposition. (Figure 6). The first step of this process is to broaden the definition of costs into a total life perspective. The concept of the total cost of ownership (TCO) has been presented in many forms including research and tools designed for analyzing business computing [12][13]. From a financial perspective, TCO represents the direct and indirect cost to purchase and utilize a product for the consumer. The sustainable products value proposition expands the set of total cost drivers.

3.1 Producer Impact: Cost of Product Development and Delivery

In general, consider the cost of these metrics to be the relative to the specific product design points chosen to meet the expected targets.

1. **Bill of Material Expense** – Typically, the primary focus of the development engineer from an expense perspective is the bill of material. This is the cost to physically manufacture the product.

2. **Relative Design concepts of delivered function, specifications and solutions** – In an effort to meet customer expected quality levels, features and functions, the engineering team creates the design specification that describes the expected outcome of the system. Typically, higher tolerances and tighter specifications can cost more to produce, but the customer may be willing to pay for it.

3. **Mean time between failure and Intervention** – The most common measure of system reliability is the **mean time between failures**. The uptime of equipment can affect productivity beyond the individual user, if the product is involved with any type of work flow. As system complexity as well as competition increase, another reliability-based metric, has become critical for the development

community. **Mean time between interventions** is also a measure of product up time, but it assumes that the system needs attention from the user (and not a warranty call). Examples in this category include clearing systems hangs/jams, changing supplies or updating the system. Complex solutions in the future will have longer lasting sub-systems, and will have intelligent operating and embedded systems.

4. **Cross Platform Compliance within Product Families** – This category is focused on the typical struggles producers face in the quest for satisfying the needs of individual customers vs. the financial benefits of focusing on the convertibility or the commonality of components or sub-systems between platforms. The ability to convert products already produced increases the value and flexibility of the supply chain team. Increasing the use or re-use of common sub-systems reduces the amount of development and verification resources required to design the product. This aspect is not only one of the key drivers that producers can use to reduce the cost of their value proposition, but it also applies directly to the improvement of the product family longevity, a key component of the environmental pillar.

5. **Generation-to-Generation Product Compliance** – The focus of this category is on enabling the producer to use existing infrastructure and intellectual property in the development of the next generation solution. Likewise, enabling the customer to use existing infrastructure and intellectual property in the transition and integration of the next generation system. Extending the platform of a product family through generation-to-generation compliance can have one of the most positive effects on designing sustainable products. This aspect is simple in concept, but becomes difficult when you integrate challenges from competitive designs, as well as the tendency of engineers to invent new systems because they can.

6. **Product Life Extension or Retirement –**. This can be a cost stream or an opportunity for re-designing or re-manufacturing the product for retirement or extended use. Either way, the development engineer takes end-of-life product aspects into consideration in the overall design. The ultimate expense for a producer can come from a consumer abandoning the use of a product before its useful end-of-life.

3.2 Customer Impact: Costs and Benefits to the Customer

Ultimately, in free enterprise markets, the consumer is the focal point of new products and the longevity of competing designs. Customers seek out solutions where they realize benefits relative to the cost of the product.

1. **Benefit of New Innovation and Solution Improvements –** This metric is counter to the others in that this driver is viewed as the aggregate benefts gained by obtaining the new solution. This can be quantified through a variety of sources such as productivity gains, improved quality or reduction in material consumption.

2. **Cost to Purchase, Install and Prepare for Use –** Beyond the initial box cost, many consumers fail to include the cost to install and create the infrastructure for new products. This includes the training and learning curve required to fully utilize the new solution. Many products are abandoned early due to a mis-match in customer expectations or skill levels.

3. **Cost of Consumables –** This expense stream covers the material or supplies needed to maintain the utility of the solution. They are typically referred to as customer replaceable units (CRU's).

4. **Cost of Maintenance and Product Intervention –** Consumers expect products to work, but understand interventions and maintenance of the system might be required. Yet, there is a cost to perform these activities that include expenses beyond the person performing the activity. Often workflow downstream is affected by the downtime of devices.

5. **Cost of Warranty Repairs -** This is the combination of warranty expense for the customer and producer, as well the cost, the consumer faces with product down time. In order to protect themselves, many customers purchase extended warranties as a precaution in case of unexpected failures.

6. **Cost of the End of Current Life Cycle –** Beyond the cost of product dispossal, there is often expenses in the activities that lead to the purchase of new equipment, as well as the removal and possible accelerated capital expense write-off of previous equipment.

3.3 Social and Environmental Impact: Cost of Product Compliance and Natural Resource Consumption

In the process of developing new products, good stewardship of our natural resources is now recognized as cost savings opportunity in addition to what more potential customer are expecting to review in the purchasing cycle. Standard reporting and certification processes are integral to the development model.

1. **Total Energy Consumption to produce and operate –** Tracking the consumption of utilities in the manufacturing process is prudent. Focusing on the effects energy consumption has on the product design often yields opportunity for increased quality or yield. In addition, consumers now track the

energy consumption of products, and it is often a critical specification for customer purchase requirements.

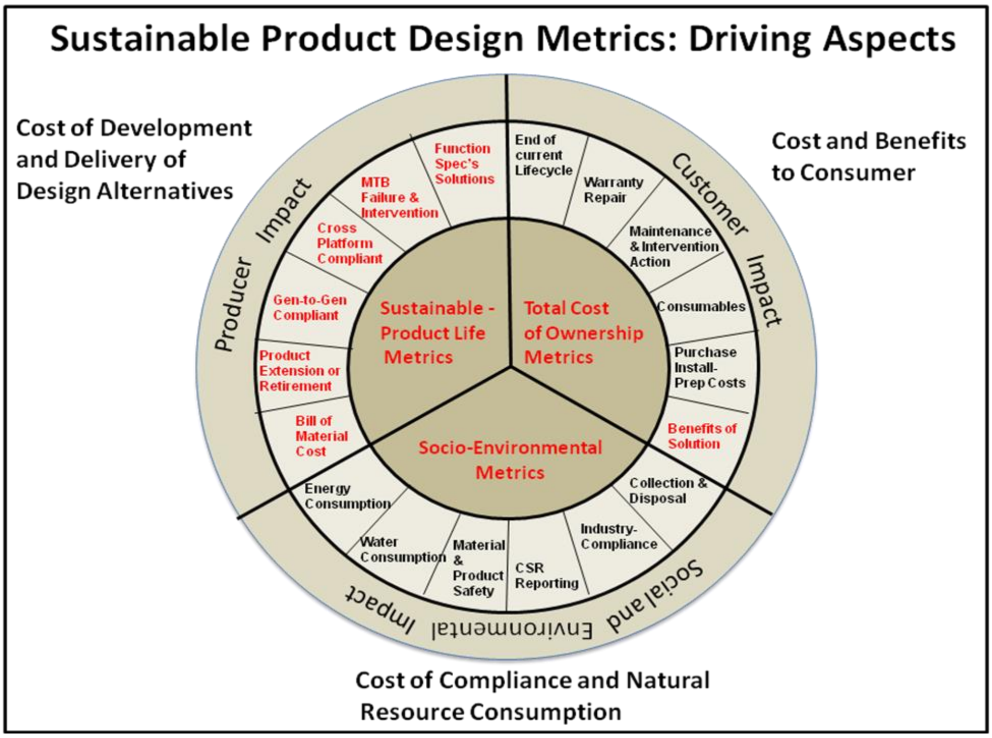


Figure 6: Detailed metrics of the cost/benefit drivers in the sustainable products value proposition.

2. **Total water consumption to produce and operate –** Energy consumption has been the central focus for engineers who seek to design for the environment. Now water consumption is also a critical aspect as the world's fresh water supplies become more acute.

3. **Product and Material Safety Compliances –** Most products require safety and material certification and approvals. In addition, depending on the product line, there can be a number of specific certifications required to sell to targeted consumers. This could include, energy, electromagnetic compatibility (EMC), acoustic or other aspects of products that affect society and the environment.

4. **Corporate Social and Environmental Activities and Reporting –** The health and safety of employees and consumers is usually first priority of producers. In addition, many corporations consider taking a proactive approach to social and environmental issues as a benefit to the overall value proposition. Today, many consumers look to producers to pass along sustainability-based metrics as part of the product delivery process.

5. **Industry specific certifications –** In addition to mainstream certification and regulatory requirements, many industries have specific regulatory requirements that are aimed at the unique social and environmental aspects that the products may have.

6. **Collection and Product Disposal -** Many new regulations require producers to reclaim or at least play a role in the handling of products at the end of life.

4 SUMMARY

In free enterprise markets, producers seek to develop products that drive a profit for their respective business as well as provide the best solution for the customer. In this process, a value proposition is developed by the producer for the consumer that is designed to overcome the risks of the business venture vs. the potential reward for both the producer as well as the consumer. Products and design platforms that are abandoned before their useful life create waste and reduce asset value for society and the environment, in addition to the producer and consumer.

The sustainable products value proposition seeks a balanced approach towards the integration of total cost of ownership, social and environmental improvements, and an expanded definition of product life drivers. The driving metrics identified in the three impact areas are focused on reducing the potential risk of relative product offerings. In the development process, engineers need to not only look at the total cost for the consumer, but also take a broader and more holistic cost view in order to identify product designs concepts that may be at higher risk for long-term sustainability and waste streams. This process is optimized, if it is conducted early in the development cycle,

The race continues between the e-gain benefits of new technology and the research for new tools that will aid in the long-term development of more sustainable products and processes. A central goal of this paper is to begin to build a new paradigm for development engineers, a paradigm that sheds light on the realization that product designs can be more sustainable from both a financial as well as environmental perspectives. By focusing on the main drivers of each sustainable value proposition aspect, the development community improves their role in creating truly sustainable value.

5 REFERENCES

[1] Moore, Gordon, E. "Cramming more components onto integrated circuits." *Electronics Magazine*, 1965: 4.

[2] Malik, Khalid. *Human Development Report 2013 The Rise of the South: Human Progress in a Diverse World.* New York: United Nations Development Programme, 2013.

[3] Friedman, Thomas L. *The World is Flat A Brief History of the Twenty-First Century.* New York: Farrar, Straus and Friedman, 2005.

[4] Laszlo, Chris. *Sustainable Value How the World's Companies Are Doing Well by Doing Good.* Standford: Stabdford Business Books, 2008.

[5] K. Ueda, T. T. (2009). Value creation and decision-making in sustainable society. *CIRP Annals - Manufacturing Technology* , Volume 58, Issue 2:681-700.

[6] T. Tolio, D. C. (2010). SPECIES-Co-evolution of products, processes and production systems. *CIRP Annals - Manufacturing Technology*, Volume 59, Issue 2:672-693.

[7] ASME, Marketing Research. *Findings of the Second Annual Autodesk/ASME Sustainable Design Trend Watch Survey.* Autodesk, 2009.

[8] Rosen, Marc A. "Engineering and Sustainability: Attitudes and Actions." *Sustianability*, 2013: Volume 5, Issue 2, pages 372-386.

[9] David Kiron, Nina Kruschwitz, Knut Haanaes, Martin Reeves, Eugene Goh. "The Benefits of Sustainability-Driven Innovation." *MIT Sloan Management Review*, 2013: 69-73.

[10] United Nations General Assembly. *Report of the World Commision on Environmental and Development: Our Common Future.* New York: United Nations, 1987.

[11] A.D. Jayal, F Badurdeen, OW Dillon, IS Jawahir. "Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels." *CIRP Journal of Manufacturing Science and Technology* , 2010: Volume 2, Issue 3, pages144-152.

[12] John Bace, Carol Roxwell, Josheph Feiman, Bill Kirwin. *Understanding the Cost of Compliance.* Gartner Inc., 2006.

[13] Ellram, Lisa. "Total Cost of Ownership: Elements and Implementation." *Journal of Supply Chain Management*, 1993: Volume 29, Issue 3, pages 2-53.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

2.3 Ecological analysis of manufacturing systems focusing on the identification of variety-induced non value adding emissions

R. Steinhilper [1], A. Kruse [1], T. Drews [1]

[1] Fraunhofer Project Group Process Innovation at the Chair of Manufacturing and Remanufacturing Technology, Bayreuth University, Germany

Abstract

Today manufacturing companies need to raise their awareness about emissions (e.g. CO_2 equivalents) and their origins within a manufacturing system. The identification of origins of emissions becomes progressively difficult because of the customer and competition driven increase in product and process variants and the corresponding high level of complexity. Therefore, it is necessary to enhance the ecological transparency in manufacturing systems. This paper introduces an assessment methodology which increases the ecological transparency through the identification of variety-induced ecological effects. Furthermore, the developed methodology enables the user to detect starting points for an ecological optimization of a manufacturing system by the use of organizational measures. The effects of influencing variables are presented on the basis of a case study. The obtained results allow manufacturing companies to reveal and reduce variety-induced non value adding emissions.

Keywords:
Ecological analysis, manufacturing systems, CO_2 emissions, variety

1 INTRODUCTION

Nowadays the majority of the manufacturing companies are forced to frequently adapt their manufacturing systems in order to meet the current and future market demands. These demands result from global and long-term economic, social and ecological developments, so-called megatrends, which impact the manufacturing industry and its systems. The most significant trends concerning manufacturing are globalization, diversified customer demands, shorter product life cycles and the shortage of resources. [1]

Especially the diversified customer demands and the shortening of product life cycles lead to an enormous increase in product variety and complexity. The development of the variety in the machinery industry is illustrated in Figure 1.

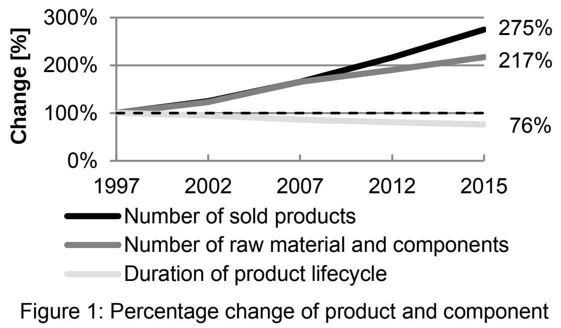


Figure 1: Percentage change of product and component variants and duration of product lifecycles. [2]

This development is one of the main reasons why processes in manufacturing systems are becoming more and more complex and economically as well as ecologically difficult to analyze. [3]

In regards to sustainable manufacturing these different developments have multiple effects and emphasize the importance of the responsible and careful usage of natural resources in manufacturing systems. On the one hand, companies have the opportunity to reduce their cost by improving their eco-efficiency despite the growing energy and raw material prices. On the other hand, the manufacturing companies can make an effort to regain non-renewable resources in product and material cycles instead of disposing them and ultimately lose their inherent value. Furthermore companies can profit from new developed technologies while purchasing an eco-friendly and carbon neutral manufacturing process. [4] [5]

In this context the global warming effect remains one of the greatest challenges of mankind [4]. The major reason behind global warming is the steadily increasing emission of greenhouse gases e.g. carbon dioxide and methane. Figure 2 illustrates the different shares of global greenhouse gas emissions in CO_2 equivalents (CO_2 eq.) for the Industry and Energy Sector [6].

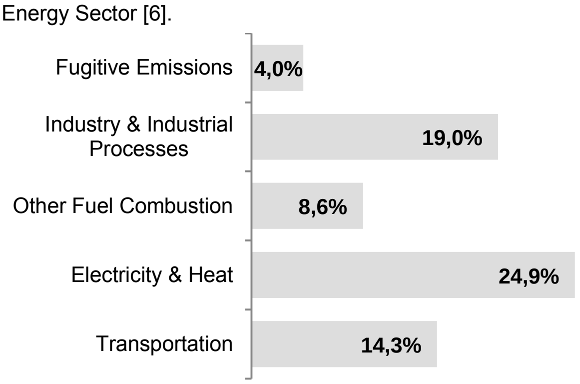


Figure 2: Share of Global Greenhouse Gas Emissions from the Industry and Energy Sector (Total: 31 Gt CO_2 eq.). [6]

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

The share of 19 % for "Industry & Industrial Processes" contains emissions which were caused by the current used methods, procedures, materials, production schedules and machinery, etc. to plan and control the manufacturing system. The presented numbers also indicate that the emissions in the area of manufacturing are still very high and therefore have a big potential for reduction.

To make use of the potential for reduction, detailed knowledge about the interdependent origins of emissions within manufacturing systems is needed. Since the knowledge about the internal and external drivers for emissions in manufacturing systems is a key element for the ecological target-oriented optimization, the transparency needs to be increased.

2 NEED FOR ECOLOGICAL TRANSPARENCY IN MANUFACTURING SYSTEMS

As previously stated, the customer demands and other global long-term developments result in a high number of product variants. The additional effort to maintain an efficient manufacturing system rises with each product variant and leads to more complex system since the complexity of these systems is directly related to the number of different product variants [7]. Within a specified system the term complexity is defined by the amount and variety of elements, their relationships and their temporal variability [8]. Based on studies, the costs for product and process complexity in manufacturing companies are up to 25 % of the total costs [9]. Additionally, 30 to 40 % of the complexity-caused costs can be linked to the manufacturing process itself [10] and the doubling of product variants can raise the costs of a product up to 30 % [11].

In terms of sustainable manufacturing not only economic but also environmental issues like emissions should be considered. The integration of environmental aspects like energy and material consumption into the planning and control of manufacturing systems offers high potentials [1], but detailed knowledge about drivers of emissions in a more and more complex environment is needed.

A specifically focused approach for the identification of variety-induced emissions in manufacturing systems does not exist so far, but several methods to assess environmental impacts of products and manufacturing processes are available, which can be adapted for the identification of variety-induced emissions in manufacturing systems.

The method Life Cycle Assessment (LCA) according to ISO 14040 and 14044 [12] has become widely-used and represents the actual state of science in the area of environmental assessment. A LCA evaluates the environmental impact of any system (e.g. product) by considering all inputs and outputs (energy and material). Normally the creation of a LCA is supported by special LCA software (e.g. SimaPro or GaBi) and the use of environmental databases (e.g. EcoInvent). Usually a LCA assesses the environmental impact of a product life cycle (cradle to grave) [13]. In order to ecologically analyze a manufacturing system and to identify variety-induced emissions a product-related cradle-to-grave approach is not applicable. Nevertheless the ISO 14040 (goal and scope definition, inventory analysis, impact assessment, interpretation) represents a suitable framework, which has to be adapted to the specific requirements [14].

Environmental impacts can be measured in several categories (acidification potential, eutrophication potential, etc.) and evaluated by the use of different evaluation methods [15]. This paper will focus on the global warming potential, which is measured in CO_2 equivalents and has become quite popular over the last years [13]. Nevertheless, the presented methodology could also be adapted for the quantification of other environmental impact categories.

3 IDENTIFIACTION OF VARIETY-INDUCED EMISSIONS

3.1 Scope of assessment and system understanding

The elements (e.g. processes or machines) of a manufacturing system can be generalized as process modules (Figure 3). Each process module is characterized by several input and output variables and aims to transform an input into a specific output. In a manufacturing system a number of process modules are coupled to a process chain. The coupling of process modules in more complex systems is identified through multiple input and output connections (e.g. parallel process chains or network structures).

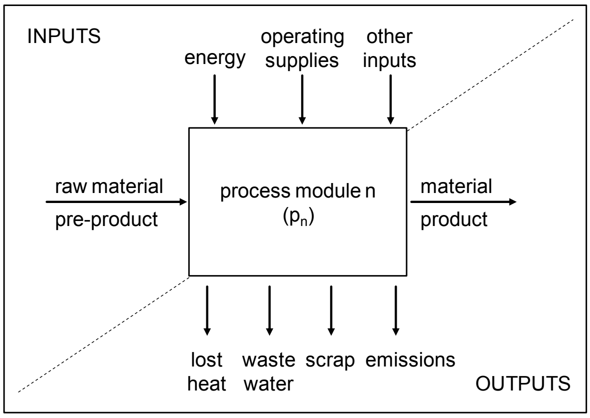


Figure 3: Generic process module [16]

The manufacturing system considered in this paper is a linear process chain, which mainly focuses on the ecological analysis of the inputs and outputs of the coupled process modules. Moreover the ecological effects of variety within the manufacturing system need to be identified in order to make the actual drivers of emissions visible.

In manufacturing systems production machinery is responsible for a major part of the emissions. The environmental impact of production machinery is mainly caused by electric energy consumption of the machine and the peripheral units. For instance, the electric energy consumption of an elementary flow of a milling process accounts for more than 95 % of the CO_2 emissions [14].

Besides the machinery other factory equipment e.g. lighting equipment or technical building equipment cause emissions as well. The latter ones do not significantly alternate with production volumes [14] and therefore are not taken into consideration in the assessment of emissions.

3.2 Assessment of variety-induced non-value adding emissions

For the assessment of variety-induced emissions of a manufacturing system only the output of process modules, which produce good parts, are considered value adding. Different output is assumed to be non-value adding and needs to be identified. Through this identification and separation of variety-induced value adding and non-value adding emissions the ecological evaluation and transparency of a manufacturing system can be improved.

Concerning a single process module within a manufacturing system the energy consumption - the main driver for CO_2 emissions - is characterized by different operating states [17]. This characteristic sequence of operating states (power profile) is schematically illustrated in Figure 4.

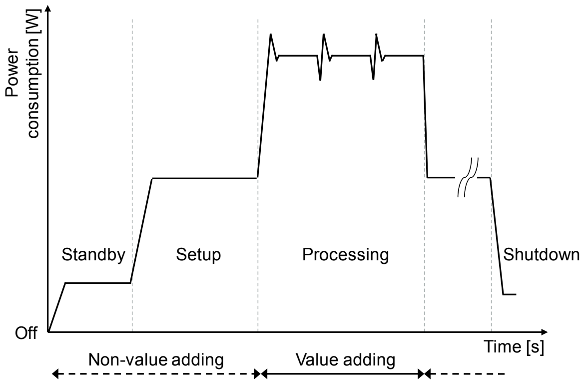


Figure 4: Power profile of manufacturing equipment with different operating states

The operating states differ from power consumption and duration. The duration of the operating state "Processing" for example is influenced by the product specification as well as the lot size, i.e. the number of equal products that are produced between two setup operations. As mentioned before, the operating states can be generally separated into value adding states (Processing) and non-value adding states (Setup, Standby, Shutdown). The ratio between value adding and non-value adding operating states is highly determined by lead times, setup times, lot sizes and the production program. This strong relation also applies for the number of product variants since the majority of these influencing variables are very closely related to the product variants.

Besides the operating states other non-value adding operations in manufacturing systems, e.g. production of process scrap and setup scrap, have to be taken into account as well. As described before, only the production of good parts is considered value adding. As a result of this, processing operations of a process module, which result in scrap later on, are considered non-value adding as well. The same applies to setup scrap, which increases with more frequent setup operations. An overview of value adding and non-value adding outputs of a process module is shown in Table 1.

Table 1 : Classification of value adding (va) and non-value adding (nva) outputs of process modules

Operating state	**Output of process module (product)**	**Classification**	
		va	**nva**
Standby	--		x
Setup	--		x
Processing	Product (good part)	x	
Processing	Process scrap		x
Processing	Setup scrap		x

In order to assess the environmental impact (CO_2 eq.) of a production program and the ecological effects of product variants, the emissions of each operating state (of each process module and product variant) have to be modeled by the use of LCA software and stored in databases as CO_2 data sets. For a discrete manufacturing process the functional unit of the environmental impact of the operating state "Processing" is one part, i.e. the amount of CO_2 equivalents caused by the processing of one specific product variant on one specific machine. The classification whether a processing operation is value adding or non-value adding depends on the output of the process module and is therefore considered later on. The functional unit of setup (as well as standby) operations is one second as the amount of emissions is related to the duration of the setup operation.

By the use of this CO_2 data sets and the classification (value adding vs. non-value adding) the ecological effects of a higher number of product variants (and therefore the production program) can be assessed and be made more transparent.

4 CASE STUDY RESULTS

4.1 Model

The manufacturing system considered in this paper consists of three generic process modules (Figure 3) which are arranged in a linear manner. The first process module is a turning machine which processes the cast parts for further machining. The two following process modules represent two sequenced milling operations on two different machines with separate characteristics e.g. specific inputs and outputs.

For purposes of the case study and especially for the evaluation of the described assessment methodology, the described manufacturing system is prototypically modeled in the discrete event simulation software Plant Simulation. On the one hand, the discrete event approach enables the consideration and detailed evaluation of different general aspects (e.g. production program) for the entire manufacturing system and its elements (e.g. machines and processed parts). On the other hand, it is also possible to factor the ecological traceability of the processed parts into the processing steps by assigning specific attributes (e.g. variant type and environmental impact) to these objects. The possibility of assigning specific attributes to certain objects and the findings of this basic model are going to be of particular interest for further examinations regarding ecological uncertainties and effects of more complex manufacturing systems (or supply chains) and its processes.

Figure 5 illustrates the schematic structure of the model as well as the three specific databases for each process module and the general database for the entire manufacturing system. The manufacturing system's database includes the product program which mainly controls the number of products and variants as well as the size and sequence of the generated lots. Furthermore the information about the point of variant creation is stored in this database. Since the variety-induced emissions are of particular interest in this paper, the following two variety-related boundary conditions are imposed:

- The product program consists of maximum five products in maximum three different product variants.
- Only when the point of variant creation is reached the corresponding process generates the number of assigned variants according to the manufacturing database.

These two boundary conditions lead to a variety maximum of 15 different product variants. Within these boundaries the model enables the user to change the numbers of variants and the point of creation.

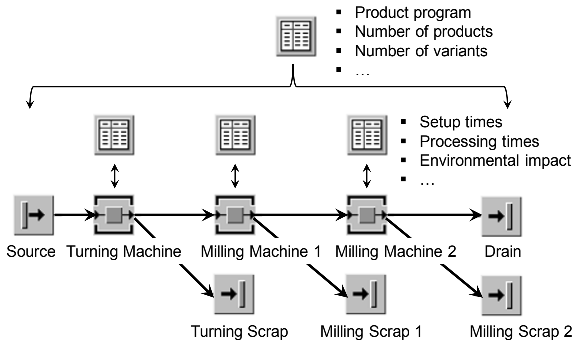


Figure 5 : Schematic figure of the manufacturing system in Plant Simulation with inputs, outputs and databases

The three specific databases for each process module combine manufacturing information (e.g. process time, setup time, scrap rates) as well as ecological information (e.g. CO_2 data sets). Concerning the ecological information the databases contain precise information about the caused emissions depending on the processing of one specific product variant on one specific machine. This ecological information can be changed by the three following influencing variables:

- Process scrap rate: This number represents a factor which influences the total number of scraped parts for the machinery.
- Setup scrap: This number represents the total amount of processed parts which are scraped during one setup operation of the machine.
- Setup time: This number represents a factor which increases or decreases the required time for setting up the machine for a new product variant.

The presented structure of the model and the discrete event approach makes it also possible to include even more influencing variables (e.g. machine failures), focus on further ecological aspects in combination with economic key performance indicators and to enlarge the scope of the considered manufacturing system e.g. by adding more complex structure of process modules.

4.2 Results of the case study

The above presented model of the manufacturing system and its corresponding influencing variables are applied in a case example. The range of the examined values of the variables and their value in the initial situation are described in Table 2.

Table 2 : Values of influencing variables and initial situation

Name of Variables	Used Values of Variables	Initial Situation
Point of variant creation	1 – 2 – 3	2
Numbers of variants	5 – 10 – 15	10
Process scrap rate	0.5 – 1 – 2	1
Setup scrap rate	0 – 1 – 2	1
Setup time	0.5 – 1 – 2	1

The initial situation serves as basis for the comparison of the sensitivity of the influencing variables in different scenarios. During the sensitivity examination of this simulation model only one variable at a time was changed in order to evaluate the sensitivity of this variable for the ecological impact of the entire manufacturing system. In the following course of the analysis the ecological impact is distinguished in value-adding and non-value adding shares. The calculation of the different shares is based on the already described CO_2 data sets for different operating states which are collected and stored in the three specific databases of the process modules.

In order to make the absolute emissions comparable to the initial situation each scenario contains a total input of 1,500 parts. For each scenario the size of the lots is based on the number of variants, equally distributed and sequentially manufactured. In Figure 6 the ecological impact in kg CO_2 eq. of three different scenarios is presented.

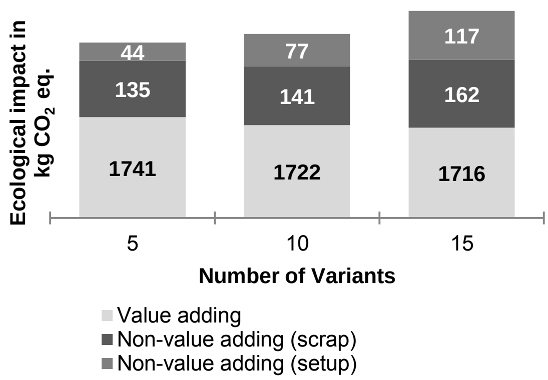


Figure 6 : Ecological impact in kg CO_2 eq. of three different scenarios of number of variants (5, 10 and 15)

The scenario in Figure 6 represents a variable configuration in which only the number of variants differs from the initial situation. The value-adding share remains approximately constant whereas the non-value adding emissions increase with a higher number of variants. In this particular case (initial number of variants: 10) the non-value adding emissions for five product variants decrease by 18 %. For 15 product variants the change is approximately a 28 % increase in non-value adding emissions.

For the further assessment of the influencing variables two different values for each defined variable are considered in comparison to the initial situation. Figure 7 and Figure 8 show the result of the sensitivity analysis for the influencing variables process scrap rate, point of variant creation, setup scrap rate and setup time for a total of 1,500 input parts and 10 different product variants. During the change of one variable all other variables maintain their initially assigned value (Table 2).

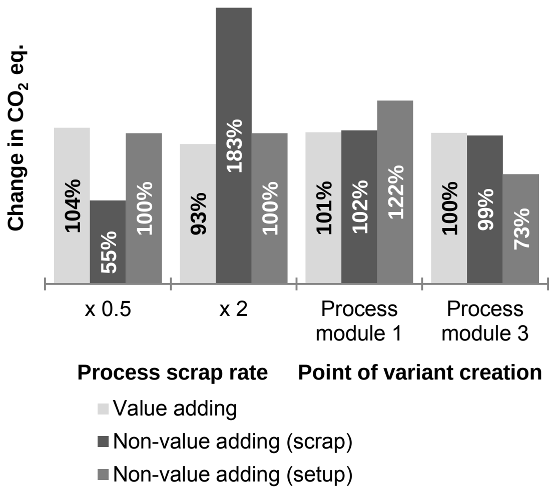


Figure 7 : Percentage change of ecological impact in CO_2 eq. for the variables process scrap rate and point of variant creation in comparison to the initial situation

The halving or doubling of the process scrap rate leads to a significant decrease (55 %) respectively an even more increase (183 %) of the non-value adding processing share. The most recognizable change in the differentiation of the point of variant creation is the variation of the non-value adding setup time. This effect can be explained by the fewer amount of setup operations in the upstream process modules.

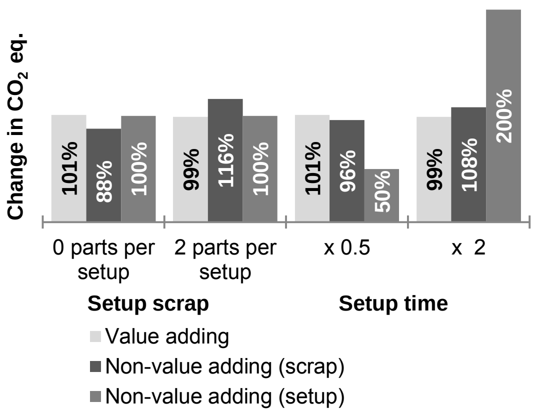


Figure 8 : Percentage change of ecological impact in CO_2 eq. for the variables setup scrap rate and setup time in comparison to the initial situation

In Figure 8 the results of the examination of the final two influencing variables are shown. The ecological effect of the setup scrap rate is based on the same origin (scrap) but slightly weaker than the process scrap rate in Figure 7. The drastic change of the ecological impact caused by the alternation of setup time can be explained by the direct impact of the setup time factor in all process modules and for each single setup operation.

5 CONCLUSION AND OUTLOOK

This paper presented an assessment methodology which increases the ecological transparency in a manufacturing system. The methodology focuses on the identification and quantification of variety-induced ecological effects. The effects of five different variables (point of variant creation, numbers of variants, process scrap rate, setup scrap rate and setup time) are examined and distinguished in value and non-value adding emissions. Especially the non-value adding emissions are highly affected by the variety-related variables (e.g. number of product variants).

The methodological approach was prototypically implemented in a discrete event simulation model. The implementation allows the examination of different scenarios through the alternation of influencing variables. Furthermore it is possible to trace single object (products) and measure their ecological contribution to single process modules as well as to the entire manufacturing system. The sensitivity of the influencing variables and their ecological contributions and effects were also verified.

As part of further research the presented model and its structure should be examined in a more complex situation. This includes the extension of the system boundaries and complexity (e.g. number of processes, interactions and uncertainties of process modules and number and variety of products) of the manufacturing system itself. Moreover further influencing variables e.g. machines failures, lot sizing and production scheduling could be considered as well. In addition to the presented sensitivity analysis detailed analysis of interdependencies between influencing variables have to be carried out in further research activities.

The further research topics also include the combined ecological and economic assessment of variety-induced effects in manufacturing systems as well as the deduction of courses of action and their evaluation in the context of traditional goals of production planning and control.

6 REFERENCES

[1] Abele, E., Reinhart, G., 2011, Zukunft der Produktion: Herausforderungen, Forschungsfelder, Chancen, Hanser, München.

[2] Roland Berger – Strategy Consultants, 2012, Mastering Product Complexity, http://www.rolandberger.us/media/pdf/Roland_Berger_Mastering-Product-Complexity_-20121107.pdf, last checked 2013-04-22.

[3] Lindemann, U., Reichwald, R., Zäh, M.F., 2006, Individualisierte Produkte – Komplexität beherrschen in Entwicklung und Produktion, Springer, Berlin Heidelberg.

[4] Seliger, G., 2007, Sustainability in Manufacturing, Springer, Berlin Heidelberg.

[5] Wiktorsson, M., Bellgran, M., Jackson, M., 2008, Sustainable Manufacturing - Challenges and Possibilities for Research and Industry from a Swedish Perspective, Manufacturing Systems and Technologies for the New Frontier, 119-122.

[6] Herzog, T., 2009, World Greenhouse Gas Emissions in 2005, Working Paper, World Ressources Institute (WRI), http://www.wri.org/publication/world-greenhouse-gas-emissions-in-2005, last checked 2013-04-21.

[7] Haumann, M., Seifert, S., Westermann, H.-H., Butzer, S., 2012, Variantenmanagement in Refabrikations-unternehmen – Assemble-to-order zur Beherrschung der Prozessvariantenvielfalt, wt Werkstatttechnik online 102 (2012) 3, 153-155.

[8] Schuh, G., 2005, Produktkomplexität managen - Strategien-Methoden-Tools, Carl Hanser, München Wien.

[9] Bick, W., Brexl-Witbecker, S., 2008, Komplexität reduzieren-Konzept. Methoden. Praxis, LOG_X, Stuttgart.

[10] Rommel, G., Brück, F., Diederichs, R., Kempis, R.-D., Kluge, J., 2006, Einfach überlegen. Das Unternehmenskonzept, das die Schlanken schlank und die Schnellen schnell macht, McKinseyClassics, Band 5, Redline Wirtschaft, Heidelberg.

[11] Jodlbauer, H., 2008, Produktionsoptimierung - Wertschaffende sowie kundenorientierte Planung und Steuerung, Springer, Wien.

[12] DIN Deutsches Institut für Normung e.V., 2006, Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen (ISO 14040:2006) - Deutsche und Englische Fassung EN ISO 14040:2006.

[13] Köhler, D., 2011, Regenerative Supply Chains, Shaker, Aachen.

[14] Steinhilper, R., Süchting, M., Kruse, A., Westermann, H.-H., 2012, How complexity in the field of production planning and control influences CO_2 emissions, Towards implementing sustainable manufacturing, Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, 495-500.

[15] Günther, E., 2008, Ökologieorientiertes Management, Stuttgart.

[16] Klöpffer, W., Grahl, B., 2009, Ökobilanz (LCA), Wiley-VCH, Weinheim.

[17] ISO 14955-1, 2012, Machine tools - Environmental evaluation of machine tools - Part 1: Design methodology for energy efficient machine tools.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

2.4 Sustainable factory profile: a concept to support the design of future sustainable industries

U. Dombrowski [1], C. Riechel [1]

[1] Institute for Advanced Industrial Management, Technische Universität Braunschweig, Germany

Abstract
The German industry caused more than a quarter (27.8%) of the total energy consumption. Factories have a high influence in resource saving during the realization of a factory and the production process. First "CO2 neutral factories" and "zero-emission factories" were realized in the last years. But they are just point solutions and these concepts are rarely used by enterprises in Germany. As part of an energy efficient optimization of factories, it is necessary to extend the focus of planning and to consider the location, the design, the integration into the environment and the potential of modern energy efficiency. Particularly the factories provides additional high saving potentials for the company. Low emission production methods or resource-efficient building practices offer opportunities for integrated environmental factory design. These approaches are integrated into the comprehensive concept "Sustainable
Factory Profile (SFP)" which is described in this paper.

Keywords:
Factory planning; Green Factory; Sustainability; Sustainable production

1 INTRODUCTION

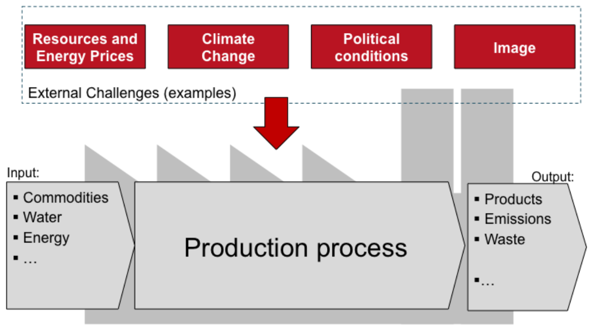


Figure 1: External challenges for the factory with focus on sustainability [3]

The factory as a place of value adding activities is forced to adapt to the requirements of the turbulent market. The customer's demand for short delivery times, innovative and sustainable products in connection with decreasing prices leads to new challenges. [1] To analyze which external challenges influence the factory, The detailed analysis of the interaction between the factory and its environment is necessary. Basically, two fields of planning can be identified for the sustainable factory planning: on the one hand the input and output and on the other hand the production processes within the factory as well as the building structure. [3]

The input is characterized, for example, by goods, water or different forms of energy; whereas products, waste and emissions define the output.

The production or manufacturing equipment, the material flow, the technical building system as well as the employees characterize the second field of planning, the building structure and the production process. With link to the organizational process, the factory is a broad field of action for sustainable optimization and design. Next to the classic challenges of the turbulent market new requirements have to be recognized during the factory planning process. The institute for advanced industrial management defines the following four external challenges as new requirements in the factory planning process: [3]

Resources and Energy prices: Energetic optimization is necessary to reduce costs.

Climate changes: The CO2 caused issues must be reduced to make a contribution to the reduction of the global warming.

Political conditions: A plurality of laws and norms with the focus on energy saving and sustainability have to be considered during the whole planning process.

Image: Energy efficiency has become an important factor of the enterprise image.

Beside these external influences also internal influences have to be taken into account. Rising costs for energy do not only have their origins in rising prices, but also in the increasing demand of energy due to automation of the production. This is caused by the application of modern energy-intensive production processes, for example by laser welding. [3]

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

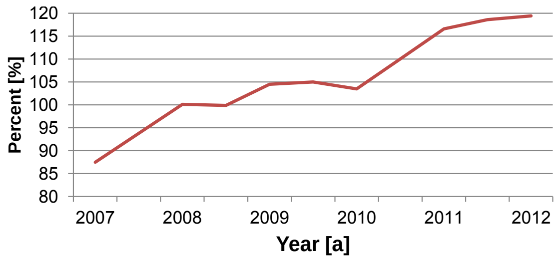


Figure 2: Development of electricity prices of industrial consumers [5]

Traditional rationalization fields like lead times, long transportation ways or inventories are considered as exhausted. The sustainable optimization as a field of activity still has a high potential for improvements. [3] More and more standards like the ISO 14001 recognize the sustainability as a field of optimization and standardization for companies. But a holistic approach on this focus is still not realized. [4]

2 EXTERNAL CHALLENGES FOR SUSTAINABLE FACTORIES

2.1 Resources and energy prices

The increase of the energy prices during the past years is one of the main arguments for many enterprises to deal with the subject of efficient energy usage. The use of electricity is becoming a relevant economic factor caused by the increasing expenses. Figure 2 illustrates the younger development of electricity prices for industrial usage in Germany. The pricing for industrial consumers in Germany increased by 20% in the last four years. A similar development has to be considered for other forms of energy. One example is the development of the oil import price. The price increased by 35% to the reference year 2008 in Germany. [5]

Compared to the German development of energy prices the situation in other European countries is more serious. For example the price for electricity in Spain has risen by 120 % in the last ten years. Furthermore, a significant rise in prices is predicted for the future. [5] Even more dramatically is the development of gas prices during the last 12 years. Compared to the year 2000 a rise in prices of 142% can be detected. [6] For this reason, the efficient use of energy during the production process becomes a competitive factor for enterprises. Decreased energy costs with constant profit allow to declining sale prices of single products by which a competitive advantage can be realized. [7]

2.2 Climate change

The climate protection by reducing the greenhouse gases defines the second external challenge, which has direct influence on the factory operation and planning. This so called greenhouse effect is in principle of natural kind and has warmed the earth's surface from below 18 degrees centigrade on an average of 15 degrees centigrade today. [8] Nevertheless, by the increase of the industrial production the development of greenhouse gases raises stronger than the forecasts predicted. As a result, the so called European Union Emission Trading System, came into effect in 2005. [9] This system includes the regulation of

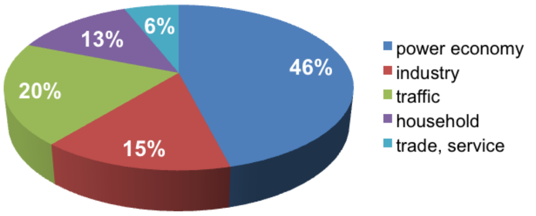


Figure 3: Distribution of CO_2 emissions in the year 2011[5]

greenhouse gases and restricts the allocation of CO_2-emission rights, or the commitment of a price for CO_2-emissions. Enterprises need to hold certificates, which are bought and charged off depending on the occurred emissions. Actually, every emitted ton CO_2 implies a payment of 100 euros.

In the sequel the industrial CO2 emissions in Germany could be continuously lowered during the last years. Nevertheless, it is of high relevance that this trend in Germany will be continued by technological and organizational changes. This statement is supported by the distribution of CO_2 emissions in the year 2011 shown in figure 3. The industry has a share of 15% of all CO_2 emissions in Germany. Next to the power economy (46%) and the traffic (20%) it is the third largest sector concerning greenhouse gases. [10]

2.3 Political conditions

A responsible use of natural resources and the protection of the environment are accepted as important development conditions worldwide. In 1992 the conference of the United Nations about environment and development (UNCED) confessed. Under the direction of Gro Harlem Brundtland the sustainability as a normative leading of "international politics". was exclaimed. Sustainability means „the present generation satisfies its needs without endangering the ability of the future generation being able to satisfy its own needs“. [11] This statement still influences the German and European (EU) legislative. In the following, only an extract of laws and norms will be introduced.

In the *Federal Immission Control Act* (BImSchG) the „protection is regulated before injurious environmental influences by air pollutions, noises, vibrations and similar processes“. Within the scope of this law other orders, administrative regulations and technical instructions are included, as, for example, the orders for an issue limitation by light-brief halogen hydrocarbons, for requiring permission arrangements or a case order directive of the EU. Requiring permission arrangements are for example, heating power works or chemical plants. [12]

Certification Systems shows no law, but a voluntary measure for the benchmark and evaluation of the factory. In this context, the evaluation should not only include ecological aspects, but should be aimed on a comprehensive consideration of the whole life cycle and all sustainable aspects like human or economic factors. A big part of this certifications system is the lifecycle assasment (LCA). The LCA is a tool to calculate the impact of a product on the environment [13] [14]

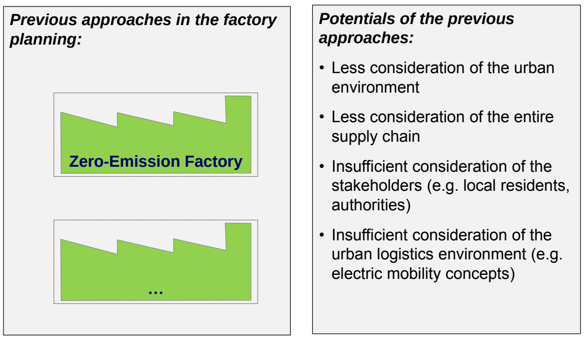


Figure 4: Previous approaches in factory planning [18]

The *Energy Saving Ordinance (EnEV)* is an important step of the energy policy and climate protection politics of the Federal Government of Germany. On this occasion, the architectural heat insulation of the building structure as well as the energy efficiency of the used technical building system (heating, airing, cooling, lighting) is considered. [15]

The environmental information law (UIG) defines, that each company in Germany is entitled to enable the access to information about the environment, which is given to an authority, to see and also to spread. [16]

Those described external challenges for the sustainable factory planning leads to new industrial and research approaches. This is caused by the rising complexity which all of this external challenges cause by considering them during the planning and operation of a factory.

3 PREVIOUES APPROACHES AND PROBLEM STATEMENT

Due to the intensified attention of the efficient use of energy and resource within the factory, the so called „zero-emission factories" or also "environmental fair factories" were developed since the 1990`s. [17] The Solvis GmbH realized one example of such a "zero emission factory" in 2002. The Solvis GmbH is a medium sized manufacturer of solar energy technology. The factory is characterized by its large collector and photovoltaic surfaces, a rapeseed oil blocktype thermal power station and a very good thermal insulation. [18] This all leads to a factory with zero emissions. Another example of an environmental fair factory is the so called „Blue Factory" built by Volkswagen in Emden. This environmental fair plant is realized for example by a modern paint shop, which uses fewer chemicals than conventional ones, a heat house operated by long-distance heating and a company-owned purification equipment. Furthermore, Volkswagen uses biomass to produce environmental fair heat supply and builds solar and wind power plants for the electric supply. [19]

Meanwhile, the potentials of a sustainable factory are not only recognized for reasons of marketing. The realization of the potentials became an established target value of the enterprise. But the main problem of those research approaches and industrial realization is, that the system boundaries of those approaches end with the factory premises. Those approaches are in most cases „isolated solutions ". (Figure 4) In order to act however effectively in the sense of a sustainable production the system borders of the past approaches have to be extended to unlock the whole potential of sustainable factories. The factory cannot be

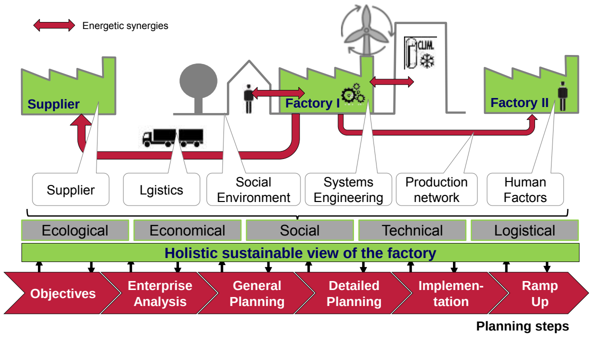


Figure 5: Holistic sustainable view of the factory [3],[20], [21]

planned and operated as an isolated system under systems, but rather has to be integrated in the whole environment. The sustainability of the factory does not end at the factory gate.

To realize a holistic view on the factory, it is necessary to recognize all relevant factors already in the planning process. Figure 5 reveals a draft of the holistic sustainable planning process of the factory. As described before, the system borders have to be extended. This includes the recognizing of the suppliers of the factory. A sustainable production process must recognize the whole value stream including all suppliers or other factories within the production network. Next to this, the influence of the social environment and human factors has to be considered during the planning, realization and operation of a sustainable factory. The basic structure of the factory planning process is not recognizing the actual situation. The classic factory planning process is structured in seven phases that are processed sequentially. [20] At the end of each phase a milestone is reached. Each factory planning project starts with the definition of objectives in the first phase. The objectives in factory planning are deduced from the corporate objectives and are specified according to the requirements of the factory planning project. Already in this phase it is necessary to define the main goals of sustainability. The project team has to gather all required information during the enterprise analysis and adapt the information for the following phases. The goal is a definition of all tasks in the project of a sustainable factory planning. The general planning can be seen as the core task of the factory planning process, because the whole factory is designed. [20] Next to the definition of objectives in this phase the basement of sustainable production is defined. Starting with the structure planning and dimensioning, an ideal layout is prepared. During the structure planning, decisions about thermal isolation or the technical buildings system are made. Those decisions have a great impact on the degree of efficiency with focus on sustainability. Based on this ideal layout, different layout variants are generated which consider restriction. These variants are evaluated according to the defined objectives. Actually, the evaluation is based on the design of the material flow or the efficient use of areas. Social or environmental optimization is actually not implemented in the evaluation process. The best variant is the input for the next phase, the detailed planning. Within the detailed planning the selected variant is put on a level of maturity for the implementation. The result is a detailed description and the visualization of all factory elements. The following phase is the implementation, where the results in the first phase are put into action. The

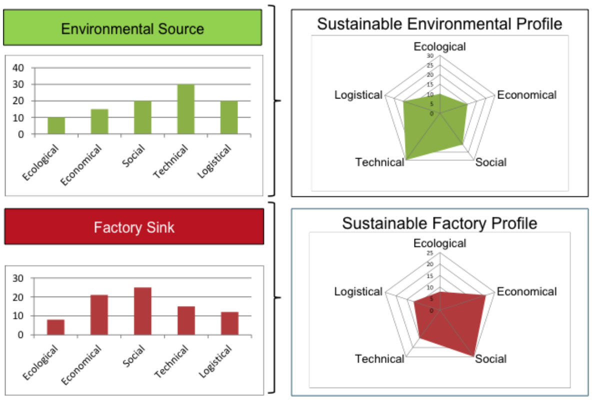


Figure 6: Sustainable Factory and Environmental Profile

implementation controlling contains the monitoring, coordination and documentation of the realization process. The factory planning project ends with the support of the production ramp up. [21], [22]

By recognizing all sustainable factors in each of those planning phases it is possible to realize and operate factories that are an integrated part in their environment. A main problem of this extended planning process is the rise of influences and restrictions to recognize within the described planning process. Sustainable planning is only useful if the basic objectives of the factory design are not compromised. Because of this, it is necessary to provide a concept, which is able to minimize all sustainable influences and factors to a useful and applicable complexity.

4 CONCEPT OF A SUSTAINABLE FACTORY PROFILE

With the main goal, to reduce the complexity of a sustainable planning process, the institute for advanced industrial management developed a concept of the sustainable factory profile. This profile supports the planning team by reducing the rising complexity caused by the integration of a holistic view of sustainable factory and a structured implementation into the planning process. The first step of this concept is the classifications of all recommend factors. Therefore, technological and logistic area extend the classic area of sustainability to the following. [23]

- Ecological area: Describes the increase and conservation of natural resources through the minimization of operational resource consumption
- Economical area: The sustaining and the increase of physical capital
- Social area: This area contains the maintenance of the internal human capital which consists of the know-how and the motivation of employees
- Technical area: This area describes the efficient planning and usage of technical equipment
- Logistical area: The logistic area describes the recognition of the whole supply chain with focus on sustainability

From each of the featured areas the factory takes resources as input for the production process (figure 1). The factory acts as a sink. In this context a sink is defined as a consumer of resources. On basis of this assumption it is possible to

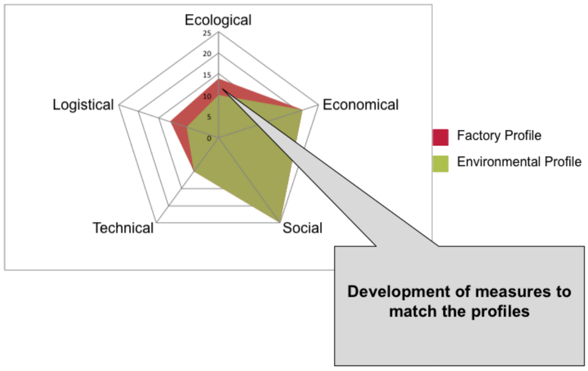


Figure 7: Sustainable Factory Profile

describe the whole factory as a combination of sinks. In the following some examples for sinks in the defined sustainably areas are shown:

- Ecological sink: The usage of fresh water
- Economical sink: The usage of capital for investments in strategic sustainable projects
- Social sink: The responsible use of employees
- Technical sink: The usage of energy to use highly efficient production or manufacturing plants
- Logistic sink: The logistic sink describes the recognition of external and internal supply of the factory. It includes the conveyance used and frequency of the supply. It defines the usage of transportation equipment like trucks or trains.

Through the structured recording of all sinks it is possible to develop a specific sustainable factory profile (figure 6). This assumes the normalization of all types of evaluation factors.

In the next step the environmental sources must be identified. Those resources are defined as source for the efficient usage in the factory. The procedure corresponds to the creation of the sustainable factory profile. The result is a sustainable environmental profile. In the following are some examples for environmental sources:

- Ecological source: If the production site has the potential of a fresh water supply by a river or similar
- Economical source: The Source of capital investment for the sustainable use in the factory
- Social source: A broad field of know how supply in the surrounding to reduce the approach road for the employees
- Technical source: A regional offer of equipment and utility supply
- Logistic source: The offer of regional suppliers to reduce the frequency of supply and the transportation way

By comparing the profiles in the next step the differences between sink and sources can be identified. The marked red area in figure 7 describes the difference/deviation. This delta defines the focus of future sustainable planning activities. In this example the logistic as well as the ecological areas contain disparities which have to be balanced. This area describes the focus which the planning team has to recognize in detail. In the next step it is necessary to develop measures and solutions to match the profiles and to find a fair balance between sink and source profile. In the following two examples are described for sustainable solutions for the logistic and ecological area.

Ecological area: If the surrounding of the factories is not able to provide the production process with renewable forms of energy it could be necessary to transform for example low temperature heat offered by surrounding factories or the urban environment into an efficient form of energy. In this case the so called heat and power installations (CHP) are one example to transform emissions in form of heat from other sources to a useful and high efficient source of electric energy for the factory. [3]

Logistic area: If the external supply of the factory is not realized by local or regional suppliers it must be a strategic goal to intense the supplier development with focus on sustainability. A regional or local supply of the factory decreases the CO_2 emissions caused by traffic.

Those examples show that the focus on those measures and solutions with the highest potential leads to new creative solutions in the field of sustainability. Due to the reducing of factors and influences, recognized during the planning and operation of a factory, the complexity can be reduced and the planning team is able to realize intelligent and creative solutions to raise the sustainability of the factory.

5 FURTHER RESEARCH

The concept shows an approach and defined structure to reduce the complexity of planning and operation of a factory with focus on sustainability. In further steps the evaluation and benchmark of the sustainable factory profile must be extended. Especially a basement of energetic profiles and date will be useful to ensure an objective result. Also a catalog of modules, solutions and measures to balance the profiles will rise the practical applicability for German and international producing enterprises.

6 CONCLUSION

Rising energy costs, new governmental restrictions like CO_2-certificates and growing environmental consciousness of consumers are new challenges for manufacturing companies. Thus, sustainability in planning and operating factories is getting more and more important to face the requirements in global competition. To make use of the whole potential of energy saving and sustainable design, it is unavoidable to extend the system boundaries through the entire value chain. The reduction of the complexity goes along with this extension. The institute for advanced industrial management developed a concept that supports the planning team to identify the main fields of sustainable planning which have to be focused. Thereby, the advantages of a sustainable planning and energy saving clearly outweigh the disadvantages of the raising planning complexity.

7 REFERENCES

[1] U. Dombrowski, S. Quack, and S. Schulze, “Development of a continuous factory improvement process for sustainable production,” Proc. of Intern. Conf. on Sustainable Product Development and Life Cycle Engineering, Busan, 2008.

[2] Hendrickson, C. T., Lave, L. B., & Matthews, H. S. (2006). Environmental life cycle assessment of goods and services: an input-output approach. Routledge.

[3] Müller, E.; Engelmann, J.; Löffler, T.; Strauch, J. (2009): Energieeffiziente Fabriken planen und betreiben, Springer Springer, Berlin.

[4] Eurostat (2013): Electricity prices for industrial consumers – Code: ten00114, online: http://epp.eurostat.ec.europa.eu.

[5] Dyllick, T., & Hamschmidt, J. (2000). Wirksamkeit und Leistung von Umweltmanagementsystemen.: Eine Untersuchung von ISO 14001-zertifizierten Unternehmen in der Schweiz. vdf Hochschulverlag AG.

[6] Eurostat (2013): Gas prices for industrial consumers – Code: ten00112, online: http://epp.eurostat.ec.europa.eu.

[7] Pehnt, M. (2010): Energieeffizienz – Definition, Indikatoren, Wirkungen, in: Pehnt, M.: Energieeffizienz, Springer, Heidelberg.

[8] Nordhaus, W. D. (1991). To slow or not to slow: the economics of the greenhouse effect. The economic journal, 101(407), 920-937.

[9] Ellerman, A. D., & Joskow, P. L. (2008). The European Union's emissions trading system in perspective. Arlington, VA: Pew Center on Global Climate Change.

[10] Umweltbundesamt (2013): CO2-Emissionen nach Quellkategorien. Online im Internet. URL: http://www.umweltbundesamt-daten-zur-umwelt.de/umweltdaten/public/theme.do?nodeIdent=2842 Stand: 05.05.2013.

[11] Brundtland, G. H. (1989). Global change and our common future. Environment: Science and Policy for Sustainable Development, 31(5), 16-43.

[12] Jarass, H. D. (2003). Bundes-Immissionsschutzgesetz: BImSchG. gen, 2, 3.

[13] Feifel, S., Walk, W., Wursthorn, S., & Schebek, L. (2009). Ökobilanzierung 2009–Ansätze und Weiterentwicklungen zur Operationalisierung von Nachhaltigkeit.

[14] Hamedani, A. Z., & Huber, F. (2012). A comparative study of DGNB, LEED and BREEAM certificate systems in urban sustainability. The Sustainable City VII: Urban Regeneration and Sustainability, 1121.

[15] Ackermann, D. I. T. (2003). Randbedingungen der Energieeinsparverordnung. In Energieeinsparverordnung (pp. 103-140). Vieweg+ Teubner Verlag.

[16] Kramer, R. (1994). Umweltinformationsgesetz. Öko-Audit-Verordnung, Umweltzeichenverordnung: Kommentar zum Umweltinformationsgesetz, Stuttgart/Berlin/Köln.

[17] Tiedemann, H. (2005). Wissensmanagement in der Fabrikplanung. Shaker.

[18] Jäger, H. (2011). Solvis Zero-Emission Factory–The ‘Solvis way’–Structure and Subject. In Glocalized Solutions for Sustainability in Manufacturing (pp. 29-31). Springer Berlin Heidelberg.

[19] Volkswagen, A. G. (2012). Auf dem Weg zur „grünen "Lackiererei. JOT Journal für Oberflächentechnik

March 2012, Volume 52, Issue 3, pp 28-33.

[20] Dombrowski, U., Riechel, C., & Schulze, S. (2011, May). Enforcing employees participation in the factory planning process. In Assembly and Manufacturing (ISAM), 2011 IEEE International Symposium on (pp. 1-6). IEEE.

[21] Richtlinie, V. D. I. 5200 (2009) Fabrikplanung. Planungsvorgehen, Verein Deutscher Ingenieure VDI.

[22] Capehart, W.C.; Turner, W.C.; Kennedy, W.J. (2008): Guide To Energy Management. Vol. 6th. Lilburn.

[23] Berkes, F., & Folke, C. (1998). Linking social and ecological systems for resilience and sustainability. Linking social and ecological systems: management practices and social mechanisms for building resilience, 1-25

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

2.5 TUT-microfactory – a small-size, modular and sustainable production system

Eeva Järvenpää, Riku Heikkilä & Reijo Tuokko
Department of Production Engineering, Tampere University of Technology, Finland

Abstract
Micro and desktop factories are small size production systems suitable for fabricating and assembling small parts and products. The development originates in the early 1990's Japan, where small machines were designed in order to save resources when producing small products. This paper introduces the modular TUT-Microfactory concept, developed at Tampere University of Technology during the past 15 years, and its applications. The sustainability of miniaturized production systems is discussed from three perspectives – environmental, economic and social. The main conclusion is that micro and desktop factories can remarkably enhance the sustainability of manufacturing from all these three perspectives.
Keywords:
Desktop factory, Microfactory, Modular production system, Sustainable manufacturing, TUT-Microfactory concept

1 INTRODUCTION

Manufacturing industry is heading towards two paradigms: *Sustainable production* and *Adaptive production*. On one hand the manufacturers need to be able to produce clean, green products and consider the ecological footprint of their production. On the other hand they need to be able to produce customized products at low cost on demand and survive with the issues of demand fluctuation, small batch sizes, short product lifecycles, global manufacturing, rapid emergence of new technical solutions and ageing workforce, while simultaneously maintaining productivity and good quality. These constantly changing requirements call for adaptive and rapidly responding production systems that can quickly adjust to the required changes in processing functions, production capacity and distribution of the orders. Dynamic response to emergence is becoming a key issue in manufacturing field, because traditional manufacturing systems are built upon rigid architectures, which cannot respond efficiently and effectively to this dynamic change. The Factories of the Future (FoF) initiative [1] aims to support European industry in meeting an increasing global consumer demand for greener, more customised and higher-quality products by helping it convert to a demand-driven industry with better adaptivity, lower waste generation and smaller energy consumption.

Miniaturization of products has been a strong trend already for several years. As the parts are getting smaller and smaller, at least partial automation of the processes will become compulsory. Although the need for such production of small-sized products has been rapidly increasing, the size scale of the manufacturing systems has not changed much. Small products are still being produced with relatively large machines, which leads to inefficient space utilization and unnecessarily high operating costs. Furthermore, these large-size production systems and machines do not provide flexibility in their location, but need to be placed in traditional large factories even though, in many cases, it would be desirable to produce the products closer to the customer.

The authors believe that small-size production systems, micro- and desktop factories, can answer to the industrial demand and challenges discussed above. Micro and desktop factories are small-size production systems suitable for the manufacture of small products with micro and/or macro size features. The development originates from the early 1990's Japan, where small machines were developed in order to save resources when producing small products, and to reduce the size of the machinery and systems to match the product dimensions. In this context, "micro" does not necessarily refer to the size of parts or their features, or the actual size or resolution of the equipment. Instead, "micro" refers to a general objective of downscaling production equipment to the same scale with the products they are manufacturing. [2]

In the late 1990's, the research spread around the world, and since then multiple miniaturized production systems, i.e. micro and desktop factories (e.g. [3][4][5][6]), modular microfactory platforms (e.g. [7][8][9]) as well as miniaturized production equipment in general, including e.g. desktop-size machining units (e.g. [10][11]), robotic cells (e.g. [12][13][14]) and rapid prototyping units, have been developed. Despite of large amount of research cited above, the level of commercialization and adoption of microfactory solutions remains still relative low. The discipline lacks of empirical cases and industrial practice on microfactory-related business. However, few commercial desktop factories have been developed (e.g. [15][16][17]). Small-size machining units exist (e.g. [19][20]) and desktop-size stand-alone automation units have been developed for different purposes (e.g. [21][22][23]).

The micro and desktop factories can bring multiple benefits against the conventional factories in terms of their sustainability. This paper will first introduce the TUT-Microfactory concept and show examples of its applications. The main emphasis on this paper is put into describing how microfactories can contribute to the sustainable manufacturing. Three most common sustainability

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

perspectives are viewed, namely ecological, economic and social.

2 INTRODUCTION TO TUT-MICROFACTORY CONCEPT

Tampere University of Technology (TUT) has a strong background on microfactory research since 1999. In this section the TUT-microfactory concept and some of its applications are introduced.

2.1 TUT-Microfactory concept

The TUT-Microfactory is a modular construction kit type concept with easy and rapid reconfigurability for different manufacturing processes of hand held size, or smaller, products. The system structure is designed with an idea that a base module (Figure 1) can work as an independent unit including all the needed auxiliary systems. The base module includes a clean room class work space, a control cabinet and the equipment needed by the clean room. Since the production module does not need a separate control cabinet, the factory can be aggregated fast and easily on a desktop table or other flat surface. This and small size of the modules enable extreme mobility of the production capacity. The outer dimensions of one base module are 300 x 200 x 220 mm and the inside workspace is 180 x 180 x 180 mm. [9][4]

The production module can be tailored to certain processes by placing process modules on top of the base module. Process module can be e.g. a robot, laser or machining unit. In addition to the top side of the base module, both sides and the front side can be left open when adjacent cells compose one integrated work space. Feeders and other devices can be placed in the opening on the sides. Examples of different configurations of TUT-microfactory modules can be seen in Figure 2. [9][4]

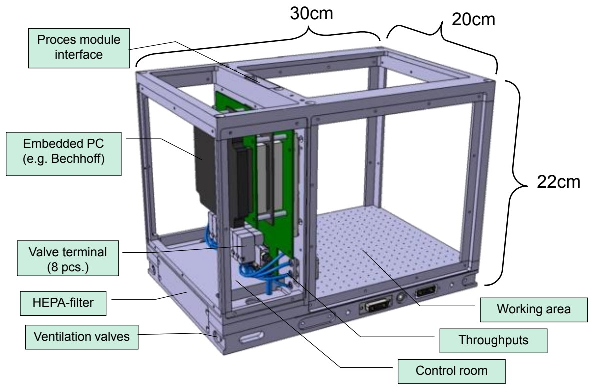


Figure 1: TUT-Microfactory base module.

All interfaces in the TUT-Microfactory concept have been designed to be as simple as possible. The base modules can be locked next to each other side by side, front by side, or front by front allowing nearly unlimited number of factory layouts, ranging from a simple line type to a freely branching one. The physical interface between two base modules includes two hybrid connectors for electrics/electronics, an interlocking system and connectors for pressurized air and vacuum. [9][4]

Due to the modular structure of the TUT-Microfactory concept and plug-and-play interfaces of the modules, it is easy to reconfigure the system to different product requirements. This reconfigurability is also supported by the fact that the small size and light weight equipment can be lifted manually without any lifting aids.

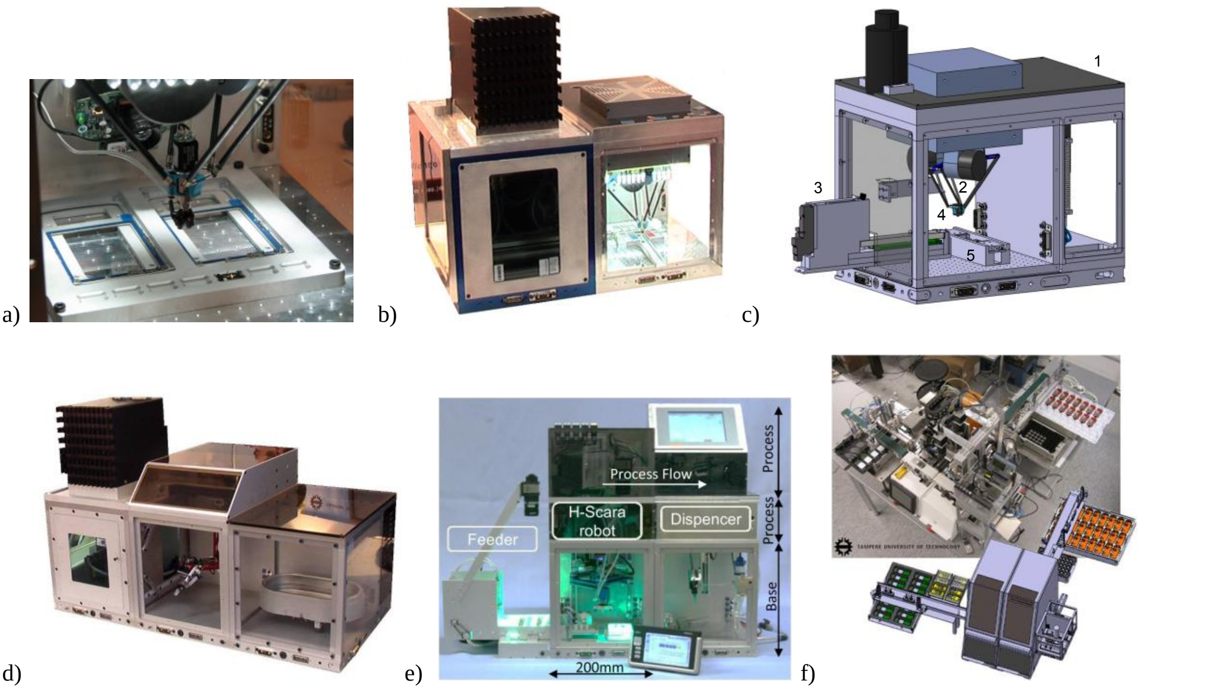


Figure 2: TUT-Microfactory applications: a) a loudspeaker assembly, b) laser marking, c) spring assembly, d) manufacturing of medical implant, e) gas sensor assembly, f) cell phone assembly. [26]

2.2 Applications of TUT-Microfactory concept

Several demonstrations, some of those shown in Figure 2, have been realized with the TUT-Microfactory concept during the past and ongoing research projects. One of the first case processes was assembly of a cell phone loudspeaker in 2005 (Fig. 2a). The assembly operation was a pick and place operation of the loudspeaker from a jig to the cell phone cover. The component size was 10.9 x 7.4 x 2 mm and weight less than 1 gram. As a manipulator a PocketDelta robot from Asyril [22] was used. [24]

The laser marking microfactory (Fig. 2b) was built as a demo for the Laser 2007 fair in Germany. The case products were personalized aluminium business cards with sizes of 4x9mm and 9x20mm. The case was a good introduction to the point-of-need manufacturing. The visitors could personalize their own business cards and get them manufactured right away. [4]

As a part of the Desk project, in 2008, the first industrial demonstration was conducted. The case process was a small spring placement in a MEMS sensor component (Fig. 2c). The small size (D 0.7 mm, L 2.54 mm) and complex shape made the spring extremely difficult to handle. The factory was built using only one TUT-Microfactory module. Besides the base module (1), a PocketDelta robot (2) was used as a manipulator, and the springs were fed by a machine vision based flexible feeding system, the Wisematic Minifeeder™ (3). The vacuum gripper (4) had a fiber optic sensor to detect the spring in the gripper. In addition, a small lead frame stepper (5) was designed to move the base components. The stepper used pneumatic actuators and an optical sensor to detect the position of the lead frame. [4]

The first process chain level three-cell demonstration was a manufacturing process of a medical implant, a laser-machined silicon rubber ear tube (D 3mm, L 5mm) (Fig. 2d). The manufacturing process consisted of machining and cleaning. Three base modules and two process modules were used in the demonstration. The first module included a 20W laser lathe with a scanner and an on-line inspection system. The on-line inspection system was used for measuring the dimensions of the tube. The second module included a 5 DOF articulated joint robot, which reached the adjacent cells as well. It was used to load the lathe and move the implants to washing. The final module included an ultrasonic washing system. [9]

The gas sensor assembly was a good introduction to different joining processes (Fig. 2e). The case product was a gas sensor (L 78mm, D 12mm), including two identical plastic frame parts, a detector in a metal package and an exciter. There were three phases in the assembly process. First, the detector was placed in the plastic frame in right orientation. Second, the exciter was placed in a correct position and angle. Third, another plastic frame was glued on top of the other. The microfactory assembly system consisted of two TUT-microfactory modules and a machine vision based flexible feeder for the frame parts. The first microfactory module was responsible for the part handling and assembly operations. A new TUT H-Scara robot was used for the manipulation. Besides the robot, the cell included a vacuum gripper, two standard 2-inch trays for component feeding, a turning unit and cameras. The second microfactory module provided the gluing process. It consisted of a low cost Cartesian TUT Linear Motor robot, a dispensing valve, an assembly jig for the base frame, a controller and an HMI unit. [25]

In the Mz-DTF project (2009-2010) the factory level integration of microfactory modules was considered and implemented. As a demonstration, a complete mobile phone assembly line was built out of commercial components and the TUT-Microfactory modules (Fig. 2f). The assembly process consisted of pick-and-place manipulation and screwing operations. The TUT-Microfactory module was used as a flexible screwing cell and larger desktop prototypes from industrial partners were used for the pick-and-place operations. The implementation was successful, but also some challenges came up. Even though handheld-size products fit perfectly into the TUT-Microfactory, the subcontractors in the electronic industry still tend to use rather large trays. Compact feeding systems, e.g. tape-and-reel, bowl and machine vision based flexible feeding, need to be further developed and accepted as an industry standard. [26]

3 SUSTAINABILITY OF MICROFACTORIES

Competitive Sustainable Manufacturing (CSM) calls for the sustainable development of manufacturing from different perspectives, most commonly mentioned being environmental, economic and social. According to [27], CSM must respond to:

- Environmental challenges, by promoting minimal use of natural resources and managing them at the best while reducing the environmental impact;
- Economic challenges by producing wealth and new services ensuring development and competitiveness through the time;
- Social challenges, by promoting social development and improved quality of life through renewed quality of wealth and jobs.

The following sections analyse how microfactories can enhance the sustainability of manufacturing from these three perspectives.

3.1 Environmental perspective

The modern production systems are expected to minimize the environmental loads the system causes during its lifetime. This sets requirements especially for the energy and resource consumption, emissions and waste generation, as well as reusability and disposal of the production system and its components.

The microfactory platforms comprise of small sized production devices. According to [2] and [31] compared to traditional larger factories, they require less factory floor space, consume less energy and raw material, and create less waste and emissions. Due to the smaller size of the overall factory, also less energy is needed for lighting, air-conditioning and heating. Also less waste heat, which needs to be cooled down, is generated.

Energy saving is one of the most often cited advantage of micro and desktop factories. For example, Kawahara et. al. [28] estimated that downscaling equipment to size 1/X reduces the consumed energy by factors presented in Table 1. They separated the energy consumption to three categories: 1) Operating energy, which is proportional to moving the parts of the equipment; 2) environmental energy, which is affected by the space needed for the equipment and the number of operators; and 3) process energy which is needed to remove material from the work piece (e.g. cutting, grinding). As can be seen from Table 1, majority of the energy is used for illumination and air conditioning and these also have the largest potential for energy savings. On the other hand, according to [28], the needed processing energy does not decrease at all when miniaturizing the equipment.

Table 1: Average energy consumption in actual factories and energy saving effect when the factories are miniaturized to 1/X [28].

	Average consumption in actual factories [%]	Energy-saving effect (1/X miniaturization)
Operating energy	13	$1 / X^3$
Environmental energy		
Illuminating	23	$1 / (1.5 * X^3)$
Air-conditioning	56	$1 / (3 * X^3)$
Processing energy and others	8	1

The case studies conducted in 2003 in Japan proved high potentials in energy and space savings by microfactories. A Desktop Factory by Sankyo for assembling motor bearings was reported to reach 98% savings in energy consumption and 95% reduction in space consumption compared to their traditional production systems [11].

Further empirical evidence of the reduced power consumption of miniaturized resources was obtained in a study conducted at TUT in 2010 by [29]. During the study average electrical power consumption of five different machines was measured in different states. The machines were: Hisac 500 OF assembly cell, Stäubli RX60 robot (with Adept controller), Mitsubishi RP-1AH, Schunk desktop scara prototype robot, and prototype of current Asyril Pocket Delta robot. The first two machines (Hisac and Stäubli) are “conventional size” machines, Mitsubishi and Schunk are small enough to be placed on a desktop, and Pocket Delta is a truly miniaturized parallel kinematic robot which can be integrated into TUT Microfactory module. Hisac, Stäubli, and Mitsubishi are commercial machines, while Schunk and Pocket Delta are prototype versions (Pocket Delta has since been commercialized by Asyril [22]).

The measured states were: 1) machine on, but motors disabled; 2) motors enabled; 3) machine running 5 x 25 x 5 mm and; 4) machine running 25 x 250 x 25 mm pick-and-place work cycle at machine’s maximum speed with zero payload. Figure 3 shows that the most energy consuming machine was Hisac cell while it was running the long pick-and-place work cycle. What is worth noting is that Mitsubishi only used about 1/6th of Hisac power consumption while it was actually faster than Hisac as shown by Figure 4. This means that with the same amount of energy, Mitsubishi can perform over six times more movements than Hisac. Power consumptions for Schunk and Pocket Delta are not directly comparable since Schunk was considerably slower than the rest of machines and Pocket Delta’s payload is only a fraction of others (around 8 g versus at least 1 kg for Hisac, Stäubli and Mitsubishi).

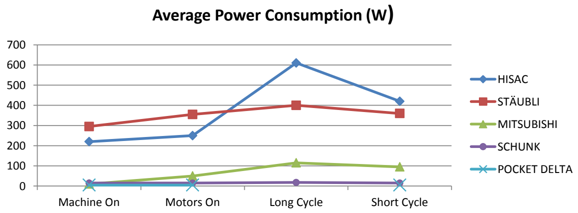


Figure 3: Average power consumption of the tested machines in different states [28].

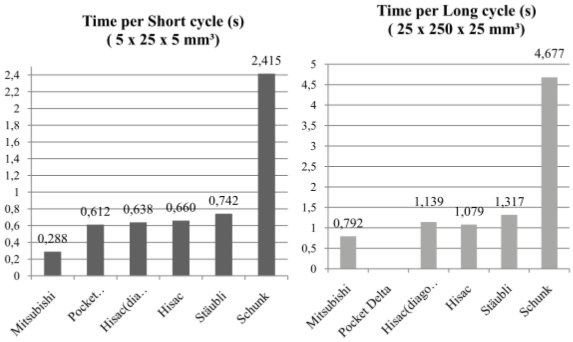


Figure 4: Cycle times of the tested machines with short and long cycles [28].

The measurements taken in TUT [29] do not directly support the estimations of Kawahara et al. [28] about the amount of energy saved. However, they do indicate that there is a great potential for operating energy savings and possibly even greater savings in, for example, air conditioning. Therefore, it can be assumed that the environmental impact is smaller for products manufactured in small size microfactories, compared to those manufactured in traditional factories.

3.2 Economical perspective

The economy pillar of the CSM calls for economic growth, global competitiveness and capital efficiency of manufacturing. From the European manufacturers’ perspective the production with the future production systems need to be cost efficient in order to be able to compete against manual work performed in the low labour cost countries.

The micro- and desktop factories offer an affordable solution to manufacturers, because of lower investment and operating costs compared to traditional larger factories. Same manufacturing capacity can be fitted into smaller space and there is a possibility to use microfactory automation to aid human worker without the need to reserve huge, expensive factory spaces. Due to their small size, microfactories don’t need big factory halls requiring heating, lighting, air-conditioning and so on. Also, as discussed in the previous section, the energy consumption and waste generation of the system itself is much lower compared to traditional larger-scale systems, leading to substantial savings in the operating costs. Microfactories allow also special controlled environment, such as a cleanroom, to be built into a small module space, eliminating the need for big expensive cleanrooms. Experiences from one full-scale desktop factory, realised in Takashima Sangyo in Japan, have shown remarkable competitiveness improvements compared to the company's earlier traditional factory: investment 1/5 and running costs 1/5 with the same production capacity [30].

In the era of customization, the desire of the manufacturers is to be able to cost-efficiently serve the customers in their individual demands and to bring the manufacturing closer to the customer. Due to the plug-and-play interfaces of the modular microfactory system components, the full scale system can be rapidly build and reconfigured to different functional and volume demands. The system set-up and ramp-up time and engineering effort for new process requirements can be radically reduced.

Especially for SMEs and start-ups circumstances like cleanroom, quality, skilled workers and investments in high-level equipment are predominant strategic and economic factors that hinder them to upscale from the lab to the full production. In addition, the unknown response from the market after launching the product, the lifecycle of the product and the evolution of the product are other issues that are taken in account when setting up the commercial production. Thus, such a modular and mobile microfactory increases the ability to rapidly follow the market dynamics by means of fast production and delivery of customised final products. Such a mobile mini-factory could also be leased (hired) for a time by a company preparing the launch of a new product, a start-up, a research institute, etc. Microfactories offer flexibility to try out new ideas without huge investments.

Small-size equipment provides improved portability of the production capacity to the place where it is needed, thus enabling new business models as well as production and logistic strategies. With the novel microfactory solutions the production doesn't need to be located anymore to traditional factories, but can be brought to the most convenient location. Few examples could be: fabricating customized shoe soles or assembling customized watches in a retail shop, fabricating spare parts in a battlefield, manufacturing products in a ship while being transported, building prototypes in an office room, teaching students about production systems in a classroom, or fabricating customized medical implants in doctor's operating room in hospital. This allows faster response to the customer requirements and more personalized service. In case of consumer products, the fact that customer can see his/her product to be manufactured or assembled, can bring competitive advantage against competitors and especially manufacturers abroad.

As discussed in the previous section microfactory can be considered as more environmental friendly way of production compared with the traditional production systems. The environmental awareness of the consumers is constantly increasing and the ecological footprint of the products starts to be more and more significant factor guiding the purchase decisions. Therefore products produced with "green" microfactories can win the game against similar products produced with traditional production systems. Implementing microfactory solutions is expected to offer potential for competitive advantage and attracting new environmentally aware customers.

3.3 Social perspective

The microfactory solutions could also have a wider societal impact for Europe and European manufacturing. First of all, they can create more attractive and safe workplaces. Secondly, they offer possibility to maintain the manufacturing jobs or even bring them back from low labour cost countries by enabling cost-efficient production of customized, green products on the spot.

From the social point of view it is important to minimize hazardous work environments, improve the ergonomics of the work environments and to pursue the efficiency, creativity and health of the workers. The risks of the manufacturing environment to the human worker are not only physical, but also psychological. For example, extremely simple, monotonous work can cause psychological issues and lack of motivation. Due to their small size, microfactories can be placed e.g. on the table of human worker to help him/her with boring repetitive tasks, tasks which require special accuracy, or tasks that are ergonomically difficult. The human can then concentrate on more interesting activities which require special skills. Compared with large production equipment, e.g. industrial robots, micro and microfactory solutions do not expose the human workers to danger. Due to small forces, for example the collisions are not fatal. Therefore, they enable safer human-machine co-operation compared to traditional large size equipment.

The microfactories can not only improve the manufacturing work environments, but also provide better service for the end customers. As the small size of the microfactory solutions allows them to be brought closer to the end customer, even to the point-of-sales or point-of-use, it ensures faster and more customized service and satisfied customers. The offered products can fit better to the individual customer's needs. For example, in the field of medical devices the customization is extremely important. Today, the customization of medical devices, such as medical implants, is still rare causing imperfect fit and possible complications. Therefore, the manufacturing of customized medical implants on the spot (in the surgeon's room or dentist's office) is expected to have a drastic impact on the quality of the implant customization and thus lead to a better fit of the implant in each patient's body. Therefore fewer complications are expected and consequently less expensive and possibly painful re-operations will be needed. This will lead to notable savings in healthcare costs and also in the time that is needed to treat individual patient. Also the quality of the treatment will be better resulting in increased well-being of the patients. Therefore, the societal impacts can be wide.

4 CONCLUSIONS

This paper discussed the sustainability of miniaturized production systems from environmental, economic and social perspectives. One microfactory concept, TUT-microfactory, was introduced in detail. As a conclusion, it can be said, that microfactory solutions can bring remarkable improvements to the manufacturing sustainability from all these three perspectives. The primary benefits are smaller investment and operating costs, as well as smaller energy and raw material consumption compared to conventional factories. The small size microfactories can be flexibly located to the most convenient locations, and modular concepts allow easy adaptivity to different demands. This adaptive "on the spot" manufacturing and the fact that microfactories are more environment friendly compared to larger factories, are expected to be the winning factors supporting the competitiveness of the European manufacturing against the low labour cost countries in the future.

5 REFERENCES

[1] EFFRA, 2012. Factories of the Future 2020, FoF Strategic Multi-Annual Roadmap, 101 p.

[2] Okazaki, Y., Mishima, N. & Ashida, K., 2004. Microfactory - Concept, History, and Developments, Journal of Manufacturing Systems Engineering, Vol. 126, No. 4, pp. 837-844.

[3] Furuta, K., 2000. The Experimental Microfactory System in Japanese National R&D project. Singapore-Japan Forum on MEMS, 23 November 2000, Singapore.

[4] Heikkilä, R., Järvenpää, E. & Tuokko, R., 2010. Advances in the TUT Microfactory Concept Development. Int. J. of Automation Technology, Vol. 4, No. 2, 2010, pp. 117-126.

[5] Kitahara, T., Ashida, K., Tanaka, et al. 1998. Microfactory and Microlathe, International Workshop on Microfactories, pp. 1–8.

[6] Park, J.-K., Lee, N.-K., Lee, D.W. & Song, J.-Y., 2007. Development of Microfactory Systems for the Next Generation - 3rd Year Report, 3th International Workshop on Microfactory Technology, pp. 5-12.

[7] Gaugel, T. & Dobler, H., 2001. Advanced modular microproduction system (AMMS), In SPIE, 29-30 October 2001. Newton, USA, pp. 278-285.

[8] Heikkila, R., Karjalainen, I., Uusitalo, J., Vuola, A. & Tuokko, R., 2007. Possibilities of a Microfactory in the Assembly of Small Parts and Products - First Results of the M4-project, ISAM, pp. 166-171.

[9] Heikkilä, R., Uusitalo, J., Heikkilä, R. & Tuokko, R., 2008. A Microfactory Concept for Laser-Assisted Manufacturing of Personalized Implants, IWMF, pp. 77-80.

[10] Kurita, T., Watanabe, S. & Hattori, M. 2001. Development of hybrid micro machine tool, 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 797-802.

[11] Okazaki, Y., 2004. Development of a desk-top milling machine with a 300 krpm spindle and a linear motor stage. In IWMF 2004, 4th International Workshop on Microfactories, Shanghai, China, October 15-17. pp. 29-33.

[12] Koelemeijer Chollet, S., Benmayor, L., Uehlinger, J.-M. & Jacot, J. 1999. Cost effective micro-system assembly automation, In 7th International Conference on Emerging Technologies and Factory Automation, pp. 359-366.

[13] Kunt, E.D., Naskali, A. T., Cakir, K. & Sabanovic, A. 2008. A Versatile and Reconfigurable Microassembly Workstation, 6th IWMF 2008, pp. 37-41.

[14] Clévy, C., Hubert, A. & Chaillet, N. 2008. Flexible micro-assembly system equipped with an automated tool changer, Journal of Micro - Nano Mechatronics, Vol. 4, No. 1, pp. 59-72.

[15] Hofmann, A., Hummel, B., Firat, O., Bretthauer, G., Bär, M. & Meyer, M. 2011. microFLEX - A New Concept to Address the Needs for Adaptable Meso and Micro Assembly Lines, ISAM 2011, 5 p.

[16] JOT Automation, 2011. JOT Automation Lean Solutions – Datasheet, 2 p. Available at: http://www.jotautomation.com/media/datasheets/final-assembly/a4_and_a3_datasheet_1_2_0_print.pdf.

[17] MAG, 2010. MAG Lean: Solutions for industry, Available at: http://www.mag.fi/products_and_services/electronics/mag_lean [Accessed December 10, 2011].

[18] JOT Intelligent Desktop Automation, 2012. JOT IDeA, http://www.jotautomation.com [Accessed October 10, 2012],

[19] Iijima, D., Ito, S., Hayashi, A., Aoyama, H. & Yamanaka, M. 2002. Micro Turning System: A Super Small CNC Precision Lathe for Microfactories, 3rd IWMF, pp. 37-40.

[20] Lin, W., Ohmori, H., Uehara, Y., Asami, M. & Ohmori, M. 2004. Development and Characteristic on the Desk-top 4-Axes Machine “TRIDER-X” for Micro-fabrication, 4th IWMF, pp. 74-79.

[21] Biohit, 2011. Biohit RobolineTM - your automate Available at: http://www.biohit.com/resource/files/media/brochures/liquid-handling/all/roboline-brochure-490100en-screen.pdf.

[22] Asyril, 2010. Rethink Micromanipulation, Available at: http://www.asyril.ch/media/PDF/Asyril_Products_E.pdf.

[23] JOT Automation, 2010. Desktop Screw Inserting Cell - Datasheet, 2 p. Available at: http://www.jotautomation.com/media/datasheets/final-assembly/j505-62_datasheet_1_0_0_screen.pdf.

[24] Heikkila, R., Karjalainen, I., Uusitalo, J., Vuola, A. & Tuokko, R., 2007. Possibilities of a Microfactory in the Assembly of Small Parts and Products - First Results of the M4-project, ISAM, pp. 166-171.

[25] Siltala, N., Prusi, T., Vuola, A., Heikkilä, R. &Tuokko, R. 2011. Modular Microfactory System for Gas Sensor Assembly”. ISAM 2011.

[26] Tuokko, R., Järvenpää, E., Heikkilä, R. & Nurmi, A. 2013. Micro and desktop factories for micro/meso-scale manufacturing applications and future visions. Applied Mechanics and Materials, Vol. 289, ISSN 978-3-03785-628-4, pp. 1-12.

[27] Jovane, F., Westkämper, E. & Williams, D., 2009. The ManuFuture Road – Towards Competitve and Sustainable High-Adding-Value Manufacturing, Springer.

[28] Kawahara, N., Suto, T., Hirano, T., Ishikawa, Y., Kitahara, T., Ooyama, N., Ataka, T. 1997. Microfactories; new applications of micromachine technology to the manufacture of small products. Microsystem Technologies, 3(2), pp. 37-41.

[29] Escribano Gimeno, L., 2010. An Overview of Microfactory Concept and Analysis of fit Principal Advantages. MSc thesis. Tampere University of Technology. 107 p.

[30] Tuokko, R. 2011. Desktop Factories – Actual Knowledge Status and Experiences from Far East. Manufuture 2011 conference, October 24, 2011.

[31] Okazaki, Y., 2010. Microfactories - A New Methodology for Sustainable Manufacturing, International Journal of Automation Technology, 4(2), 2010, pp. 82-87.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany
CIRP

2.6 Environmental indicators applied to reality of Eco-Industrial Park (EIP)

M. Felicio[1], D. C. Amaral [2]
[1] Department for Production Engineering, São Paulo University, Brazil
[2] Department for Production Engineering, São Paulo University, Brazil

Abstract
The Eco-Industrial Parks (EIP - Eco-Industrial Park) emerged as a new model of spatial organization for industrial arrangements. An important feature for an EIP is the adoption of the concept of industrial symbiosis (IS), in which companies reuse waste to reach a closed system, reducing environmental impact. The article describes an analysis of the environmental indicators used in EIPs through a systematic literature review (RBS). Results indicated that there are proposals to evaluate the waste stream and the symbiosis of an EIP through detailed indicators, which capture the need in a particular moment of time. The paper describes, compares and analyzes these proposals. As a result, it was shown that they have limitations described and exemplified in the text.

Keywords:
Eco-Industrial Park (EIP), Indicators, Industrial Symbiosis (SI), Systematic Literature Review (RBS).

1 INTRODUCTION

The Eco-Industrial Parks (EIPs) and Industrial Symbiosis (IS) process are in the field of Industrial Ecology, as fundamental tools, that harmoniously integrate the vision of the closed loop in a business ecosystem.

Seeking better utilization of by-products and waste treatment, the EIPs support the development of industrial symbiosis, highlighting the process as the main activities to be developed in an EIP.

The decisive factor for the success of an EIP is the determination of an organization to manage the EIP, known as an broker, whose role is to introduce the concept of symbiosis and encourage this practice. In addition, he is responsible for attracting viable businesses and gain the cooperation of all regulatory agencies. According Massard and Erkman [1], its function is to inform stakeholders on the issue of resource efficiency and waste exchange of promoting the sharing of experiences on the management of the flow identified, evaluating and implementing potential IS. But the most significant challenge is to define instruments direct to brokers that support systems and management practices in EIP [2] [3] [4] [5].

Some authors [2] [6] [7] [8] [9] have used indicators as a decision tool in EIPs, once they are able to provide information about physical systems, social and economic, allowing to analyze tendencies and cause-effect relationships over time.

The purpose of this paper is to examine indicators used in EIPs through a Systematic Literature Review (SLR).

2 METHODOLOGICAL ASPECTS

This work consists of an exploratory analysis of the state of the art of the Eco-Industrial Park concept and indicators used in EIPs. The methodological procedure adopted in this article was based on the Systematic Literature Review and followed the proposal of Conforto, Amaral and Silva [10]. The aim was to verify the existence of indicators that analyze, evaluate or collaborate in the management of an EIP.

The method used to carry out the SLR is divide into four stages. In the first stage, involving planning, the activities performed were: definition of the problem, definition of research goals, selection of primary sources, construction of search strings, definition of inclusion and qualification criteria and definition of the search methodology generating a research protocol. In the second stage, comprising execution, searches, data collection and application of inclusion criteria took place. The third stage, involving results analysis, consisted of the interpretation of the articles, summary of results and content analysis. Lastly, in the conclusion and introduction, articles were registered, consolidating the SLR results and developing theoretical models.

In this sense, we developed a protocol for a systematic literature review, which defined criteria for inclusion / exclusion of articles, and criteria for selection of indicators. The intention was to answer, especially the following question: What indicators are used to assess, analyze and contribute to the management of an EIP?

3 A REVIEW OF RELATED LITERATURE

3.1 Overview – Industrial Symbiosis Process in EIPs

The industrial symbiosis (IS) comprises industrial and commercial activities including the process of byproducts exchange as the main characteristic, seeking economic development, sound environmental planning, meeting the needs of neighboring communities and proper land use. Chertow [11] defines IS as the involvement of industries traditionally separated in a collective approach for competitive advantage including physical exchange of materials, energy, water and byproducts. The keys to industrial symbiosis are

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

collaboration and synergy possibilities offered by geographical proximity.

There are currently few studies in the EIP literature and its definition is still undergoing an evolution process. Among the main materials, we highlight documents concerning specific EIP projects which provide a basis to further scientific studies. In practice, their implementation is even more emergent.

An eco-industrial park is:

"(...) a community of industries, businesses and services located in a common property. Its members strive to achieve the best environmental, economic and social performance through cooperation and environmental and natural resources management. Working together, the business community seeks a collective benefit greater than the sum of individual benefits the company would reach if it only improved its individual performance". Indigo Development [12].

The IS and EIP themes intertwine in that the process of IS is considered one of the main activities to be developed in an EIP. Based on thorough research of thirteen projects that were carried out by groups of students during the two years, Chertow [13] stated that the EIPs are a part of industrial symbiosis, highlighting it as a key feature.

The clarification of the advantages of IS is essential in the formation of EIPs, because works as attractive to implement the process in these environments. Benefits such as reducing the use of virgin materials, reduce pollution, reduce transportation costs of raw materials and waste management, greater community involvement, green marketing, sustainability, increase energy efficiency, increase the amount and types of process with a market value are recognized by many authors as Chertow and Lombardi [14], Geng et al. [6], Lowe [15] and Tudor et al. [16].

EIPs has been seen as an opportunity for companies to reduce their waste, recover values and achieve economies of scale in their production processes. Seuring [17] observes that increased competition in the international market has been a major driver for the establishment of EIP.

There is a worldwide interest in the implementation and development of EIPs. According to Indigo Development Institute [12], the public and private sectors began more than one hundred (100) EIP projects in Asia, Europe, Africa, North America, Latin America and Australia. The initiatives are at different stages of development. The reason of this different is the disparities of the economic reality of each country. In developing countries, such as Brazil, the government has supported projects to build new industrial parks. In already developed countries and linked directly to the current economic crisis, this new trend has brought the adaptation of existing industrial parks, seeking to transform them into EIPs.

An important issue in the analysis of these projects is that, in general, they do not adopt all elements featuring an EIP. Peck [18] reveals the absence of a specific methodology that defines what an EIP, and points out that the development of a clear definition would not only maintain their legitimacy, but also allow the park adjustments relating to their own local circumstances. Industrial parks have used this gap to classify themselves as EIPs.

Another question at issue concerns the lack of tools that support systems and management practices in EIP [2] [3] [4] [5], and as a result, difficult to accurately measure the development and operation of these parks.

3.2 Eco-Industrial Park as Dynamic Systems

There are several studies that suggest the use of methods and tools such as Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and environmental indicators to characterize an EIP, measure the level of reuse of waste, eco-efficiency and environmental impacts in industrial parks. [6] [7] [9] [19]. However, these efforts have limitations that should be considered.

The tools have important features: result in absolute numbers, are accurate and can be compared across parks with different calculations. However, in the case of LCA for example, there is wide variation in the use of the criteria in the assessment of environmental impacts, requiring time to analysis and making it difficult to compare historical data with varying types of impacts.

This type of tool reflects a static view according to Chertow Ehrenfeld [20], once it provides a picture of the situation of the EIP in a given time, enabling to capture and "freeze" the situation in terms of the level of impact is EIP at a given time. These proposals also allow for future design a theoretical situation "more" symbiotic, indicating changes in processes and products to a set of specific companies. The limitation of this approach is in the form of analysis of the problem, where the EIP is viewed under a static point of view, not allowing initiate a set of actions to promote changes in EIP towards improving the situation identified. This is noted by the authors of the more recent proposals such as Wang, Feng and Chu [21] that admit the instability as a serious barrier to the appropriate development and progress of industrial symbiosis. Furthermore, tools are complex and requiring time for application and analysis.

The solution to this issue, and for the appropriate development of the field of industrial ecology, would be view the EIPs as dynamical systems [20]. Under this approach, the industrial environment is considered a dynamic system (complex adaptive), composed of companies and actors whose aims and goals are constantly changing, once they depend on market conditions and seek to reconcile various issues, such as economic benefits and their own desires. Abreu, Figueiredo Junior and Varvakis [22] explain that firms are open systems and are subject to change values and ideologies prevailing in the society in which it operates.

Chertow [23] shows that the industrial ecosystems have a strong dependence on market forces, and subject to rapid change, non-linear and discontinuous changes of direction, and must be seen as complex adaptive systems. For Tuddor et al. [16] companies can, over time, taking different paths and change their goals, thus affecting the functioning of the entire chain, developing a certain "fragile" system potential, once the dependency relationship between the companies do not necessarily ensure their survival, as the natural symbiosis. The company's move to another park may represent the biggest advantages that the current condition symbiotic can offer. The interaction in industrial parks is an opportunity in this regard.

4 SYSTEMATIC LITERATURE REVIEW – INDICATORS USED IN ECO-INDUSTRIAL PARKS

Some papers discuss about the use of environmental indicators for EIPs. The indicators are applied in the evaluation of the companies individually, or in the evaluation of the park as a system. According Sendra, Gabarrell e Vicent [8], there are many problems arise when implementing Industrial Ecology in industrial areas. They show that indicators are necessary and useful in order to objectively reflect and measure the constant evolution of this areas, it can structure and simplify systems data.

In an attempt to convert an existing industrial area in Spain in EIPs, the authors adapted the methodology Material Flow Analysis (MFA) proposed by Eurostat [24], widely used to analyze the social metabolism industrial and evaluate industrial parks and companies, and complemented with indicators of energy and water. The authors, through a case of study, used this indicators to detect companies with high consumption or inefficiency and evaluate the efficiency of some strategies in the conversion of an industrial area in Catalonia (Spain) in an EIP. The use of indicators allowed the detection of critical points of the system, such as resource consumption (Direct Material Input, Total Material Requirement, Water Input Total, Total Energy Input) and the use of own resources system (domestic versus imported), generation waste (or Total wastes Generation Material Inefficiency) and efficiency (Eco-efficiency or Eco-Intensity).

According to the authors, the process of transformation of an industrial park in EIP is slow and progressive, requiring the same goals among individual companies and the collective system and the use of indicators to measure this evolution.

Geng et al. [6] presented the model of circular economy based in China and discussed environmental performance of projects in the industrial areas. The authors explain that the implementation of EIPs has emerged as a project to support the policy of Chinese circular economy, currently having over fifty pilot projects in progress. The authors presented four groups of indicators applicable in Chinese industrial parks to measure their eco-efficiency: economic development indicators, indicators of material reduction and recycling, pollution control indicators and indicators related to the management of the park.

Later, Geng et al. [7] proposed a system of twelve indicators categorized into four groups. Four indicators for the outflow and four consumption category, two indicators for the integrated resources and two for the disposal of waste and emissions. The MFA was selected as the primary method to develop such indicators and other tools such as eco-efficiency indicators, were also taken to measure the environmental performance related to economic performance, especially for the use of water, energy and waste generation. The authors conclude that the application of this system may contribute to greater attention from local governments on environmental issues and to achieve economic, environmental and social benefits. However, there are significant barriers, such as how to implement this system, the lack of specific indicators of SI and social indicators, and the lack of studies that show significant results of deploying this system of indicators.

Kurup and Stehlik [9] applied in a practical case, an evaluation model for EIPs to measure the benefits of industrial symbiosis in the environmental, social and economic dimensions. To evaluate the efficiency of the method, the authors developed indicators to measure some aspects of each dimension. To measure the environmental benefits, the indicators used were: resource conservation, resource security, water contamination, dust emission, noise and air emission impact. To measure the social benefits, the indicators used were: productivity, retention of employees, job security / creation, sharing occupational health and safety programs' investment in research and development, sharing of infrastructure and technology, sharing of human resources, employee relations management, information sharing between companies, perception of communities in regards to environmental health, communication about the project in the community, partnership of educational opportunities for school children, employment opportunities, complaints from community, sharing of information between community and industries, level of understanding about IS projects among the community, opportunities of public relations, networking between industries and communities. And finally, to measure the economic benefits, the indicators used were: business opportunities, infrastructure for industries, for public infrastructure, labor costs, equipment costs, raw materials costs, compliance costs, permit costs, cost of penalties / fines and cost of future liabilities.

The authors highlighted the lack of studies to measure the relationship between stakeholders and study the common rules that help organizations and communities to work more efficiently.

Pakarinen et al. [19] analyzed the development of sustainability in a case of industrial symbiosis in Finland during the historical period of 1890-2005. The study is the practical application of the IS condition analysis system proposed by Sokka et al. [25]. Through this system the authors have identified and selected measurable indicators for each the four conditions. For each of the system conditions was chose to focus (non-renewable resources, emissions to nature, land use, impacts on human health and society) that steered the selection of indicators. For non-renewable resources were selected indicators related to metal recycling, waste and utilization of byproducts and fuel use. To emissions were considered specific chemical emissions and the treatment and recycling of these wastes. For land use used the amount of logging and minerals. And finally, impacts to human health and society, the authors considered the risks to health with specific products and social benefits through cooperation with the municipality. For the authors, the indicators presented in the case study can be a starting point for the analysis of aspects involved in the process of industrial symbiosis.

According Pakarinen et al. [19], the development of industrial ecosystems can be differentiated into three stages : Type I is an undeveloped system in which processes are linear—there are no feedback flows yet. In Type II a few feedback flows exist but the degree of exchange is still limited. In Type III material flows are almost cyclical: waste is used as a resource for other system components, therefore little waste leaves the system. The historical period presented in this study was framed in stages of development of industrial ecosystems and analyzed according to specific indicators focus on the condition of systems. The indicators used in this study showed that the case symbiosis developed in many ways towards better sustainability

Zhu et al. [2] developed a method of selection of companies interested in participating in an EIP which included the implementation of a system of indicators, providing a quantitative method to assess the adequacy of the company in an EIP to increase efficiency and stability systemic. The system consists of seven primary indicatiors, that are the key factors to consider by stakeholders of EIPs, and twenty-seven secondary indicators, that measure the profiles of each primary indicator. The indicators constitute a hierarchical structure. The indicators were divided according to a perspective based on the park and a perspective based on individual companies. For the first perspective, the authors considered as primary indicators: Matching with existing industrial chains, Park carrying capacity and Park environment performance improvement. For the second perspective, were considered indicators: eco-design, economic benefit, resources utilization and pollutants production.

Through the case study in a Chinese EIP, the authors applied the system of indicators in five candidate companies to assess their functionality these companies. The Analytic Hierarchy Process (AHP) method was used to generate weights to the seven primary indicators. For the authors, the access indicator system provides honest evaluation items for the stakeholders. In the indicator set, the most important one is the index of matching with existing industrial chains because it measures the enhancement of industrial symbiosis.

The authors concluded that the system provides a direct evaluation for the stakeholders of EIP.

5 DISCUSSION

The development of EIPs and support tools for brokers of industrial parks is still an emerging issue. In this sense, the work identifies the environmental indicators used that contribute to the management of an EIP.

The survey indicated that all studies consider symbiosis as a key element in the theoretical definition of EIPs. Also presented the results of an RBS which identified environmental indicators used for the evaluation of eco-industrial parks. It was identified the following characteristics: the scope of environmental dimensions treated is significant, and the focus has been on assessing the environmental performance combined with economic performance.

The analysis of these studies indicated that the proposed indicators measure the performance of a park at a given moment and discuss the accuracy and precision of these measures. They assist in the evaluation of the symbiosis, but indirectly by assessing specific aspects of metal recycling, nature emissions, fuel usage, use of waste.

Therefore, they do not explore how these data can be used for decision making of brokers, or serve as an incentive to change the status of the symbiosis, specifically. For this would need to consider the dynamic changes over time. This is called a static perspective in this research.

The maintenance of the studies in this perspective can be an obstacle to the improvement of industrial symbiosis, because more than measure, it is necessary indicators that can serve as incentive instruments, capable of generating a dynamic environment for collaboration and improvement in the level of symbiosis.

6 CONCLUSION

The Table 1 is a summary of key indicators used in EIPs.

Considering these results, we can conclude that this research identified an important theoretical gap: the need for proposals for indicators or indicator systems that consider a dynamic view of the problem, and indicators that go beyond measuring performance in a given time and may: 1) show the evolution of IS in the park over time, and 2) to compare the contribution of each company for this performance, serving incentive for the brokers of the park.

The work also indicates a contradiction studies. Although all articles and definitions recognize the process of industrial symbiosis as the main element of an EIP, the proposed indicators do not consider this perspective changes over time, which would be essential for the incremental improvement of IS in the park. We propose future research that can generate a parameter for evaluating the level of symbiosis over time.

7 ACKNOWLEDGMENTS

We thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) Brazilian agency and the University of São Paulo, for the financial support for this study.

Table 1. Result of Systematic Literature Review

Authors	Indicators
Sendra, C.; Gabarrell, X.; Vicent, T., 2007	Adapted the methodology Material Flow Analysis (MFA) proposed by Eurostat [24], widely used to analyze the social metabolism industrial and evaluate industrial parks and companies, and complemented with indicators of energy and water
Geng, Y.; Zhang, P.; Côté, R.; Fujita, T., 2009	The authors presented four groups of indicators applicable in Chinese industrial parks to measure their eco-efficiency: economic development indicators, indicators of material reduction and recycling, pollution control indicators and indicators related to the management of the park.

Geng, y.; Fu, J.; Sarkis, J.; Xue, B., 2012	System of twelve indicators categorized into four groups. Four indicators for the outflow and four consumption category, two indicators for the integrated resources and two for the disposal of waste and emissions.
Kurup, B.; Stehlik, D., 2009	To measure the environmental benefits, the indicators used were: resource conservation, resource security, water contamination, dust emission, noise and air emission impact. To measure the social benefits, the indicators used were: productivity, retention of employees, job security / creation, sharing occupational health and safety programs' investment in research and development, sharing of infrastructure and technology, sharing of human resources, employee relations management, information sharing between companies, perception of communities in regards to environmental health, communication about the project in the community, partnership of educational opportunities for school children, employment opportunities, complaints from community, sharing of information between community and industries, level of understanding about IS projects among the community, opportunities of public relations, networking between industries and communities. And finally, to measure the economic benefits, the indicators used were: business opportunities, infrastructure for industries, for public infrastructure, labor costs, equipment costs, raw materials costs, compliance costs, permit costs, cost of penalties / fines and cost of future liabilities.
Pakarinen, S.; Mattila, T.; Melanen, M.; Nissinen, A.; Sokka, L., 2010	Through this system the authors have identified and selected measurable indicators for each the four conditions. For each of the system conditions was chose to focus (non-renewable resources, emissions to nature, land use, impacts on human health and society) that steered the selection of indicators. For non-renewable resources were selected indicators related to metal recycling, waste and utilization of byproducts and fuel use. To emissions were considered specific chemical emissions and the treatment and recycling of these wastes. For land use used the amount of logging and minerals. And finally, impacts to human health and society, the authors considered the risks to health with specific products and social benefits through cooperation with the municipality.
Zhu, L.; Zhou, J.; Cui, Z.; Liu L., 2010	The system consists of seven primary indicatiors, that are the key factors to consider by stakeholders of EIPs, and twenty-seven secondary indicators, that measure the profiles of each primary indicator. For the first perspective, the authors considered as primary indicators: Matching with existing industrial chains, Park carrying capacity and Park environment performance improvement. For the second perspective, were considered indicators: eco-design, economic benefit, resources utilization and pollutants production.

8 REFERENCES

[1] Massard, G.; Erkman, S., 2007, A regional industrial symbiosis methodology and its implementation in Geneva, Switzerland. In: Conference proceeding for the 3rd international conference on life cycle management, University of Zurich, Irchel, Zurich, 27-29.

[2] Zhu, L.; Zhou, J.; Cui, Z.; Liu L., 2010, A method for controlling enterprises access to an eco-industrial park. Science of the Total Environment, 4817-4825.

[3] Chiu, A. S. F.; Yong, G., 2004, On the industrial ecology potential in Asian developing countries. J. Cleaner Prod; 12(8-10)1037-45.

[4] Sopha, B. M.; Fet, A. M.; Keitsch, M. M.; Haskins C., 2010, Using systems engineering to create a framework for evaluating industrial symbiosis options. Systems Engineering, v. 13(2),149-160.

[5] Oh, D. S.; Kim, K. B.; Jeong, S. Y., 2005, Eco-industrial park design: a daedeok technovalley case study. Habitat International, v. 29 (2), p. 269-284.

[6] Geng, Y.; Zhang, P.; Côté, R.; Fujita, T., 2009. Assessment of the national eco-industrial park standard for promoting industrial symbiosis in China. Journal of Industrial Ecology, v.13(1), 15-26.

[7] Geng, y.; Fu, J.; Sarkis, J.; Xue, B., 2012, Towards a national circular economy indicator system in China: an evaluation and critical analysis. Journal of Cleaner Production, v. 23, 216-224.

[8] Sendra, C.; Gabarrell, X.; Vicent, T., 2007, Material flow analysis adapted to an industrial area. Journal of Cleaner Production, v.15, 1706-1715.

[9] Kurup, B.; Stehlik, D., 2009, Towards a model to assess the sustainability implications of industrial symbiosis in eco industrial parks, Progress in Industrial Ecology – An International Journal, v. 6(2), 103-119.

[10] Conforto, E. C., Amaral, D. C., Silva, S. L., 2011, Roteiro para revisão bibliográfica sistemática: aplicação no desenvolvimento de produtos e gerenciamento de projetos, In: 8º Congresso Brasileiro de Gestão de Desenvolvimento de Produto. Porto Alegre, RS.

[11] Chertow, M. R., 2000, Industrial Symbiosis: Literature And Taxonomy, Annual Review Energy Environment, 25:313-337.

[12] Indigo Development, 2005, Eco-Industrial Parks (EIP). Disponível em: <http://www.Indigodev.com/Eco Parks.html>, Acesso em: 10 Abr. 2011.

[13] Chertow, M. R., 1999, The eco-industrial park model reconsidered. Journal of Industrial Ecology, v. 2(3), 8-10.

[14] Chertow, M.; Lombardi, D. R., 2005, Quantifying economic and environmental benefits of co-located firms. Environmental Science & Technology, v. 39(17), 6535-6541.

[15] Lowe, E. A., 2001, Eco-industrial park handbook for Asian developing countries. A Report to Asian Development Bank, Environment Department, Indigo Development, Oakland, CA.

[16] Tudor, T.; Adam E.; Bates, M., 2007, Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): a literature review. Ecological Economics.

[17] Seuring, S. A., 2001, A framework for green supply chain costing: a fashion industry example. In: Sarkis, J. (Ed.), Green Manufacturing and Operations: From Design to Delivery and Back. Greenleaf Publishing, Sheffield (UK),150–160.

[18] Peck, S., 2002, When is an eco-industrial park not an eco- industrial park. Journal of Industrial Ecology, v. 5, 3-5.

[19] Pakarinen, S.; Mattila, T.; Melanen, M.; Nissinen, A.; Sokka, L., 2010, Sustainability and industrial symbiosis – the evolution of a finnish forest industry complex. Resources, Conservation and Recycling,1393-1404.

[20] Chertow, M. R., Ehrenfeld, J., 2012, Organizing Self-Organizing Systems – Toward a Theory of Industrial Symbiosis, Journal of Industrial Ecology, 16:13-27.

[21] Wang, G.; Feng, X.; Chu, K.H., 2013, A novel approach for stability analysis of industrial symbiosis systems. Journal of clean production, v. 39, 9-16.

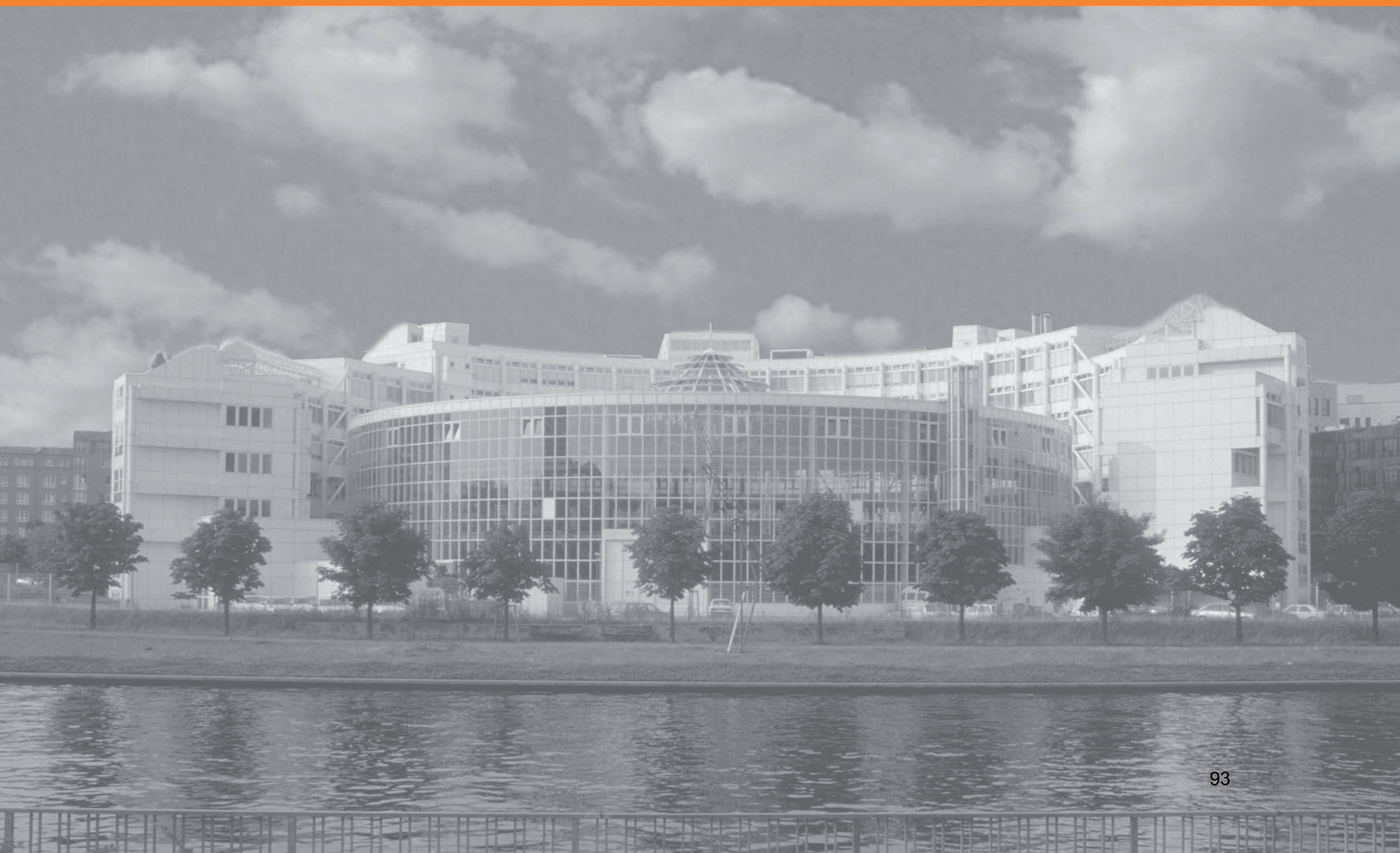
[22] Abreu, M. C. S.; Figueiredo junior, H. S.; Varvakis, G., 2002, Modelo de avaliação da estratégia ambiental: os perfis de conduta estratégica. Read – Edição Especial 30, v. 8, n. 6.

[23] Chertow, M. R., 2009, Dynamics of geographically based industrial ecosystems. In: The dynamics of regions and networks in industrial ecosystems, edited by M. Ruth and B. Davidsdottir. Cheltenham, UK: Edward Elgar.

[24] Eurostat – European Statistic, 2001, Economy-wide material flow accounts and derived indicators. A methodological guide. Luxembourg: Office for Official Publications of the European Communities.

[25] Sokka, L.; Lehtoranta, S.; Nissinen, A.; Melanen, M., 2011, Analyzing the environmental benefits of industrial symbiosis: life cycle assessment applied to a finnish forest industry complex. Journal of Industrial Ecology 15 (1), 137-155.

Session 3
Resource Utilization



GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

3.1 The role of resource efficiency in engineering education

A. Abu Hanieh [1], A. Hasan [1], S. AbdElall [2], P. Krajnik [3]
[1] Faculty of Engineering, Birzeit University, Palestine
[2] Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany
[3] Faculty of Mechanical Engineering, University of Ljubljana, Slovenia

Abstract
The purpose of this paper is to address various issues of resource efficiency in the perspective of engineering education in the Middle East and North Africa (MENA) region, with particular focus on Occupied Palestinian Territory (Palestine). First, the paper reviews the concept of resource efficiency from several perspectives including energy, electricity and water related challenges, material management and solid waste management. Then the current state of the education and training is discussed along with some details regarding the developed resource accounting perspective for engineering education. Open knowledge platform is foreseen to aid the transition from problem to solution, bringing engineering education up front to tackle the resource efficiency challenges in the MENA region. Finally, capacity building through university graduates is considered as an important mechanism for raising awareness in resource efficiency.

Keywords:
Resource efficiency, renewable energy, water treatment, waste treatment, engineering education.

1 INTRODUCTION

Some countries in the Middle East and North Africa (MENA) suffer from limited natural resources especially water, materials and energy. Water shortage is considered as one of the main problems in the MENA hence measures and policies to use it efficiently are urgent in this region. Shortage in conventional resources of energy is another major problem for some countries like Jordan and Palestine; this could be partially solved using sustainable and renewable energy resources. On the other hand municipal solid waste as well as material wastage in the industries is a major challenge for resource efficiency and competitiveness.

Resource is an economic or productive factor required to accomplish an activity, or as means to undertake an enterprise and achieve desired outcome. Resource efficiency needs a consistent definition, between nations, disciplines and business sectors. According to the European Commission, resource efficiency allows the economy to create more with less, delivering greater value with less input, using resources in a sustainable way and minimizing their impacts on the environment. Similarly, the United Nations Environment Program (UNEP), defines resource efficiency as to ensure that natural resources are produced, processed, and consumed in a more sustainable way, reducing the environmental impact from the consumption and production of products over their full life cycles. Although there are many definitions of resource efficiency, almost all agree that the three most basic resources are land, labor, and capital; other resources include energy, entrepreneurship, information, expertise, management, and time. Resources considered in this paper include: water, material and energy. Resource efficiency can be improved through optimization of productive use of resources at all stages of the production/consumption cycle. Inadequate use of resources creates waste. Resource efficiency hence aims to maximize the useful usage of resources and minimize waste. This goal can be achieved by controlling the efficiency in stages of: design, production and consumption.

Designing a product that saves the resource consumption is one approach for resource efficiency. Producing the product using efficient processes is the second approach. Efficient use of the product produced is the third approach. A three-step approach for analyzing the potential for resource efficiency improvement are [1]:

- The first step involves the analysis of the current consumption of materials, and the presentation of a breakdown of the consumption.
- In the next step efficiency improvement measures are identified and their effects on material and energy consumption are calculated.
- In the last step the measures are evaluated and the total results are calculated.

Reducing requirements for production of new (virgin) material would lead to reduced rates of extraction of natural resources, reduced energy and water demand, reductions in emissions and other environmental harms, and potentially has national political advantages through offering a reduced dependence on imports and increased self-reliance. Options

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

to reduce emissions, while meeting market demand for materials, through energy and process efficiency. This ambition has already driven strong interest in the pursuit of [2]: increased recycling; material substitution; powering industry with low-carbon electricity; carbon capture and storage. Additional material efficiency strategies, that might provide a significant reduction in the total environmental impact of the global economy include [3], [4]: component re-use; longer life; more intense use, repair and re-sale; product upgrades, modularity and remanufacturing; options for change that will use less materials to provide more services [5], [6].

Engineering education is one of the major drivers behind resource efficiency. Building required skills, human capital as well as offering the technical/technological innovation to improve sustainability. The paper outlines Open Knowledge Platform for Resource Efficiency (OKPRE), being proposed to aid educational efforts, creating and sharing knowledge and raising awareness to achieve changes in societal behavior, production and consumption patterns, and to set up for more inclusive participation with regard to resource efficiency. In this respect the OKPRE is intended to aid education and raise awareness by enabling a multi-stakeholder participation, dialogue, exchange of best practices and partnership for resource efficiency.

2 PROBLEMS IN RESOURCE EFFICIENCY

2.1 Energy challenges in MENA region

Energy acts as a main indicator of industrial activity and improved standard of living. GDP is correlated easily with energy per capita consumption or domestic material consumption influencing resource productivity. For non-fossil fuel producing countries in the MENA region such as Palestine energy supply can be a limiting factor of growth and prosperity. Maximizing the use of the available energy resources on one hand and utilizing renewable energy resources on the other hand will be the wise option for such countries. This issue becomes extremely important in view of 70% increase in demand for primary energy over the next 20 years.

2.2 Electricity and water in MENA region

In Palestine, the electricity grid reaches 99% of population unlike other countries in the region. Even in the oil rich countries the electricity grid and supply is not 100%. Palestinians in the West Bank do not generate their electrical power. The total power purchased is around 98%, the bulk is supplied by Israel, and Jordan provides around 6%. In Gaza Strip, Israel supply 50% and Egypt supply 7%. The rest is supposed to be generated by the Gaza 140-MW Power Station (GPS). Main problem in Palestine is the equality of electricity and it duration. Interruptions and break downs are very frequent in winter time. In Gaza Strip situation is much worse due to the unavailability of fuel for the GPS, such that it operates only a few hours a day. People depend for most of the time on diesel generators generating electricity at a high price and polluting the environment. Other constrains when it comes to energy is the price and the cost. Electricity prices in Palestine are very high because almost all energy is imported from Israel at a relatively high cost and then taxed by the Palestinian Authority. The average selling price of electricity is 0.115 €/kWh. There are no subsidies; energy therefore takes a large part of the household income of Palestinians. The average annual income per capita in Palestine is 1,030 €; the electricity bill amounts to about 10% of the family income [7].

In general the MENA region suffers from shortage of water. Countries like Jordan and Palestine in particular suffer from continuous increase of the water scarcity. Climate changes and environment issues are adding to already present political concerns over the water problem [9]. Palestinian water abstractions have declined over the last ten years, as the result of the combined effect of dropping water tables, Israeli restricted drilling, deepening and rehabilitation of wells. Water withdrawals per capita for Palestinians in the West Bank are about one quarter of those of the Israelis, and are continously declining over the last decade. By regional standards, Palestinians have the lowest access to fresh water resources as shown in the table 1 below [10].

Table 2: Per capita availability of renewable water resources in Jordan basin (Sources: World Bank, 2007, PWA, [11]).

Country	m^3 per capita per annum
West Bank	75
Gaza	125
Jordan	200
Israel	240
Lebanon	1200
Syria	1500

2.3 Material management

Material management is an engineering technique concerned with planning, organizing and control of flow of materials from their initial purchase to destination [12]. Material management aims at getting the right quality and quantity of supplies in the right time and place at the right cost. The objectives of material management refer to material planning, purchasing, procuring, storing and inventory control. On the other hand, material management helps in organizing supplies, distribution and quality assurance of materials. In general, the best procedure for material management flow is outlined in Figure 1 that represents a material management cycle [12].

(MENA) region suffers from shortage in different types of materials that are considered vital for development of this region. Therefore, it is even more important to use adequate management techniques to manage the most important material resources like petroleum and construction materials to sustain the resources for a longer period. Stone, marble and aggregate make up to 50% of materials used in construction. Managing the life cycle of this material will improve the efficiency of this resource and the regional economy as well [13]. The rest of materials used in construction are divided into metals and non-metals. The most widely used metal is steel followed by aluminium while the non-metals relate to rubber, plastic, and wood. Petroleum producing countries in MENA depend on oil and gas, responsible for 90% of their GDP [14].

Figure 1: Material management flow diagram

2.4 Solid waste management

Waste increases with the increase in population and development. To minimize the adverse impacts of waste on environment and humans, it is necessary to manage and prevent waste. Management process is handled by planning and implementing a complete programme for waste collection, transport, disposal and recycle/reuse. Waste prevention is better than waste management. Waste prevention can be done by designing longer life products, reducing packaging and reusing materials and products. The second process is recycling and composting. Recycling can be done by recollecting used materials such as paper, plastic, glass and metals and reuse or remanufacture them. Some organic wastes are rich in nutrients and can be used to improve soils in composting process. Recycling process reduces solid waste quantities and on the other hand, it creates job opportunities. Solid waste that cannot be prevented or recycled must be treated by disposal in land filling or combustion. Land filling can be done to produce methane for energy purposes. Controlled combustion is used to reduce size of waste and produce energy [15].

Figure 2 presents a flow chart for waste management process in which products are either returned back to be reused as new products or turned into green energy to be used for human requirements.

Implementation of sustainable waste management practices requires an understanding of different social, economic, and legal/regulatory issues involved, such as:

- **Institutional level:** Establish a national policy and pass laws on solid waste management standards and practices.
- **Social level:** Encourage citizen participation in all phases of waste management planning to help gain community awareness, input, and acceptance.
- **Economic level:** Calculate the initial capital investment requirements and long-term operating and maintenance costs associated with the various waste management activities.
- **Technical level:** Include geological factors, transport distances, and projected waste generation in siting and design considerations.
- **Environmental level:** Establish procedures to verify the protection of groundwater and drinking water.

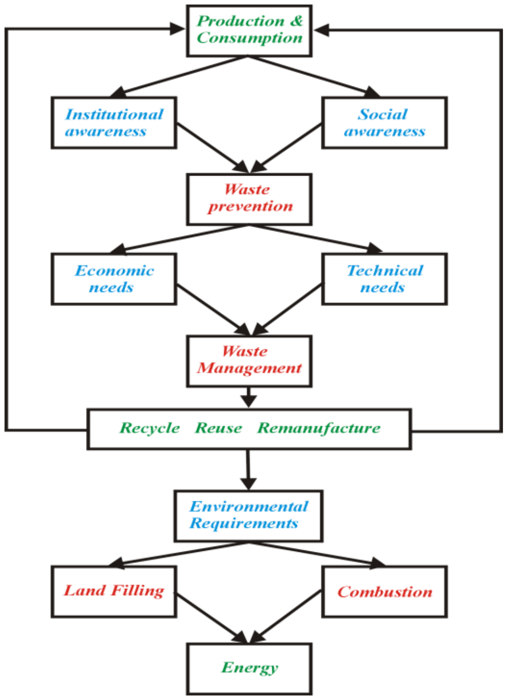


Figure 2: Waste management flow chart

3 EDUCATION AND TRAINING

MENA societies need solutions for resource efficiency to attain different national goals for sustainable development. Exploitation of the synergies across the societies: higher education institutions, NGOs, investors and professional bodies are likely to bring resource efficiency to practice. Education is fundamental to the achievement of the resource efficiency, therefore modernization of engineering education and lifelong learning training is needed.

3.1 Innovative education methods

Higher education is considered as one of the most important reasons for emigration from MENA to Western countries. In order to avoid this brain drain, it is necessary to improve higher education system in the MENA including employing new modern learning techniques. The modern learning theory states that “Student is the centre of learning process while teacher is just a facilitator”. Figure 3 presents the distribution of MENA students abroad. It is clear that the majority of students is distributed amongst the EU countries.

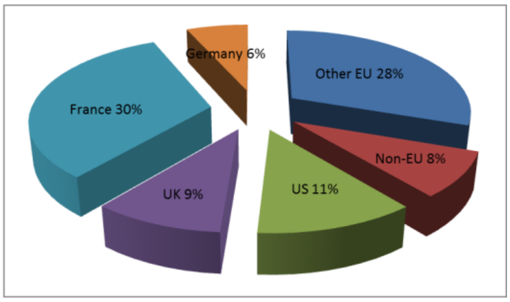


Figure 3: Distribution of MENA students studying abroad (Source: UNESCO 2008).

Project Based Learning (PBL) is considered as one of the best methods for engineering education. PBL is based on using practical projects on which students work in groups to implement scientific theories on real problems. Here, students are divided into groups where each group works on a specific project or problem to be solved. Problems are selected to solve problems facing local society. Community Based Learning (CBL) is another learning technique based on integrating students into local community and reflecting the impact of education on this community. CBL can be applied on engineering education as well as other scientific and humanity disciplines.

Cooperative (CO-OP) education is considered one of the most important learning methods for Engineering, Information Technology and Business educational disciplines. CO-OP can be divided into two main techniques: In-class cooperative learning and in-market cooperative learning. It helps students to share ideas and opinions, ask for reasoning, work in teams, encourage everyone to participate and energize groups. On the personal level, it leads students to learn monitoring, observing, intervening and processing [16]. In-market CO-OP learning aims at developing partnership with local market and industry and opening new opportunities for students and graduates in their future career and business.

3.2 Lifelong Learning

Lifelong learning (LLL) is a very wide concept and has been defined by different people depending on the national context. It can involve the following forms: adult learning; non-traditional students in a formal and informal environment; supplementary (non-degree) study programmes; career reengineering programme. The activities carried out under LLL can vary from part-time, distance, adult, mixed-mode, electronic and open learning. Lifelong learning can be provided either by HEIs or by private professional associations. Nevertheless, it is required from the governments to lay out rules and measures for the implementation of LLL in the frame of cooperation between higher education and industry [17].

4 3.3 RESOURCE ACCOUNTING PERSPECTIVE FOR ENGINEERING EDUCATION

This paper presents a newly developed model for engineering education. The proposed model for engineering education is based on the Integrated Definition Function (IDEF) Modelling technique. The engineering education model shown in Figure 4 is based on considering “Engineering Education” as the main function to be modelled. This function is supported mainly by six variables: inputs, outputs, controls, mechanisms, information and dynamics. These variables are connected as follows:

Outputs: The main outputs of the engineering education process are: Knowledge - is the most important output on which most of other outputs depend. Graduates - engineers from all disciplines should obtain the necessary level of education that fits to the needs of the local society. Opportunities - Having good education process leads to opening new opportunities, jobs, and business. Development - This educational technique helps in the development of local industry and society leading to improving the life level of people.

Inputs, Information, Controls & Mechanisms: The main inputs to the engineering education process are: Curriculum – Preparing curriculum for engineering programme requires taking inputs from state of-the-art literature, best practices and case-studies. To support traditional educational techniques, Cooperative education should be applied to assure sustainability. Students – are the centre of education process. Besides to theoretical information, students need to be aware of issues related to their disciplines. Assessment is used to control and evaluate the level and adequateness of these students. Students need to attend Lifelong Learning courses during and after their study period to stay up to date with all recent advances. Facilitators – In modern educational theories, teachers are called facilitators because their main job is facilitating ways for students rather than lecturing. Facilitators get their experience from global contacts with higher educational institutions and industrial partners. They transfer knowledge obtained through these contacts to the education process. The level and appropriateness of this knowledge is measured and controlled by taking feedback from local society. Resources – All previous items require resources to be accomplished. These resources are decided referring to the experimentation requirements and should be related directly to the existing resources of the local society. Resource efficiency methods should be aided here by an Open Knowledge Platform for Resource Efficiency (OKPRE).

This platform plays the role of intermediate between HEI and society.

Dynamics: The dynamics deteriorating Engineering Education process take their input from Market needs. The variables affecting these dynamics are: Theory, Research and Practice used to vary Awareness of students. The output of these dynamics is the Knowledge given to students.

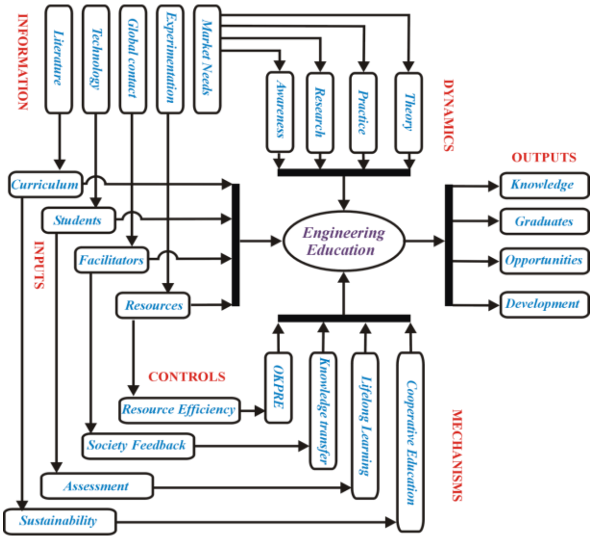


Figure 4: Developed model for Engineering Education

5 OPEN KNOWLEDGE PLATFORM FOR RESOURCE EFFICIENCY

In order to achieve a sustainable, resource efficient society, behavioral change among government authorities, private sector, organizations as well as individuals is necessary. Education is needed to promote sustainable societal behavior and enhance understanding and skills for the development of a resource efficient, sustainable society. In general, there is a wide variety of tools available to support an uptake and implementation of resource efficiency, such as [18]:

- Studies and analysis of trends in current resource efficiency and consumption and production patterns.
- Policy frameworks for stakeholder cooperation in resource efficiency.
- Economic analysis and business models for resource efficiency in the private sector.
- International expert networks and platforms, and links between education providers and policy bodies as well as government agencies.
- Capacity building tools for sustainable management, operations approaches and product choices for governments, civil society organizations, etc.

Education is one of the key elements to achieve a resource efficient society, therefore a tool that facilitates information exchange, knowledge assessment, raising awareness and an adoption of best practices is needed. This is addressed through the Open Knowledge Platform for Resource Efficiency (OKPRE). The OKPRE is a digital forum, ICT open data knowledge hub combining open social media, distributed knowledge creation and sharing tools in order to create new and innovative practices of resource efficiency.

6 RAISING AWARENESS

Raising awareness will be partially incorporated into the OKPRE to drive the transformation of markets and to ensure a gradual adoption towards resource efficiency. The needed transformation requires an open exchange of ideas among students, interdisciplinary researchers, enterprises, business executives, and the public. To raise awareness and gain impact, a forum for multi-stakeholder participation, dialogue, exchange of experience, best practices and partnerships for resource efficiency will be incorporated to OKPRE with the aim of making awareness open and hence more accessible to a broad base of stakeholders in Occupied Palestinian Territories (OPT) and the wider MENA region, covering public institutions, private sector and civil society. The following steps may offer a way forward for developing an outreach for resource efficiency:

- Conducting needs assessment: Awareness actions are most likely to succeed if they are developed in cooperation with major stakeholders and individuals from society at large to complement governmental development strategies.
- Developing national/regional resource efficiency awareness actions: The major issue in this step is to implement what needs to be achieved (as per identified needs) and how to engage partners and stakeholders in a broad and open effort.
- Dissemination through workshops for stakeholders: Dissemination should communicate the findings of the needs assessment; agreed list of priority activities; recommendations for implementation; and produce a strategy paper (published action plan) for establishing resource efficiency awareness program.
- Implement priority activities: In the case of raising awareness, activities may range from web and radio/TV programs and launching PR campaigns.
- Strengthen and sustain the outreach: Sustainability is always a major challenge for outreach programs. Funding and collaborative partnerships need to be maintained over the longer term.

Another imminent approach is to share and analyze the feedback of the novel, even though regionally focused, resource efficiency approaches to engineering education within international forums, such as this conference.

7 CONCLUSIONS

This paper discussed engineering education in the MENA region with the focus on integrating resource efficiency knowledge in this process. Statistics about water and energy problems in the MENA region were given for case studies from Palestine. Proposed solutions for waste management and material management were discussed and demonstrated. Novel techniques of engineering education was debated, concluding that using new educational strategies like CO-OP, Problem Based Learning and Lifelong Learning can lead towards more sustainable society. A new educational model based on IDEF modelling technique was depicted. This model involves most of the necessary inputs, outputs, mechanisms, controls and information required for the advancement of educational process. The dynamics shown in the model represent the factors that deteriorate the learning process and its influence on the level of knowledge obtained. The OKPRE was introduced to support practices for sharing educational knowledge, to achieve changes in production and consumption patterns, and to raise awareness regarding resource efficiency through open access approach.

ACKNOWLEDGEMENTS

This research was conducted within the ME-Eng-Tempus project “Middle Eastern Partnership in Sustainable Engineering”.. This project has been funded with support from the European Commission. This publication reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

8 REFERENCES

[1] Worrell, E., A. P. C. Faaij, et al. 1995. An approach for analysing the potential for material efficiency improvement. Resources, Conservation and Recycling **13**(3–4): 215-232.

[2] Allwood, J. M., M. F. Ashby, et al. 2013. Material efficiency: providing material services with less material production. Philosophical transactions. Series A, Mathematical, physical, and engineering sciences.

[3] Allwood, J. M. and J. M. Cullen, 2012. Sustainable materials with both eyes open, UIT Cambridge Ltd.

[4] Gutowski, T. G., S. Sahni, et al. 2013. The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand. Philosophical transactions. Series A, Mathematical, physical, and engineering sciences, **371**.

[5] Wang, C. and G. Seliger, 2012. Water Footprint Method for Application on Industrial Products. 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey.

[6] Weinert, N., S. Chiotellis, et al. 2011. Methodology for planning and operating energy-efficient production systems. CIRP Annuals - Manufacturing Technology **60**(1): 41-44

[7] Palestinian National Authority; Palestine Energy Authority; The Power Sector, 2009, Letter of Sector Policy, Ramallah. Economical, Technological and Environmental Impact Assessment of National Regulations and Incentives for RE and EE: Country Report Palestine, RECREEE.

[8] Palestinian National Authority; Palestinian Central Bureau of Statistics, 2008, Energy Consumption in the Palestinian Territory. Annual Report, Ramallah.

[9] Palestinian Energy Authority, 2009, Energy Efficiency Improvement & Greenhouse Gas Reduction Project (EIGER), Implemented by Palestinian Energy Authority in Cooperation with UNDP & GEF. Renewable Energy Projects Implemented in Palestine.

[10] The World Bank , 2009, Middle East and North Africa Region, Sustainable Development.

[11] Shuval, Hillel and Hassan Dweik (Eds), 2007, Water Resources in the Middle East. Springer Berlin. pp 454.

[12] Patel, K and Vyas, C, 2011, Construction Materials Management on Project sites, National Conference on Recent Trends in Engineering & Technology, Gujarat, India.

[13] Abu Hanieh, A, AbdElall, S. and Hasan, A, 2012, Stone and Marble Sector in Palestine, Model for Sustainability, 10th Global Conference on Sutainable Manufacturing, Istanbul, Turkey.

[14] Al Khalifa, A-J, July 2011, Economic Development of Petroleum Producing Countries in MENA Region, Drillers and Dealers, Special Article.

[15] Agha, S. 2006, Optimizing Routing of Municipal Solid Waste Collection Vehicles in Deir El Balah – Gaza Strip, Islamic University Journal (Series of National Studies and Engineering), Vol. 14, No. 2, pp 75-89.

[16] Southwest Consortium for improvement of Mathematics and Science teaching, 1994, Classroom Compass – Cooperative learning, Volume 1, Number 2.

[17] European Commission, 2010, Focus on Higher Education in Europe 2010, the Impact of Bologna Process, Eurydice.

[18] United Nations Environment Programme. Resource Efficiency and Sustainable Consumption and Production, http://www.unep.org/resourceefficiency/Tools/tabid/55537/Default.aspx. Web. 15 Apr. 2013.

3.2 Upgradable system opportunities in order to rationalize materials

O. Pialot [1], D. Millet [1]

[1] LISMMA / Supmeca Toulon / Quartier Mayol, Maison des technologies 83000 Toulon - France

Abstract
Design of more sustainable products is a fundamental priority in our society. New opportunities for facilitating the dissemination of the remanufacturing approach or the Product-Service Systems, or for increasing the lifetime of product (three ways for rationalizing of materials) are proposed by the integration of upgrades, functional enrichments brought to the product. This paper aims to show the need of product upgradability through a concrete study focused on four hypotheses:
• H1- Upgradability concept requires a potential of disposed devices which still works.
• H2- Upgradability concept requires a need for adaptability of product towards user needs.
• H3- Upgradability concept requires a need for adaptability of product versus the competition.
• H4- Upgradability concept is consistent with an accumulation of problems.
The first results show the necessity to consider a new sort of "evolutionary" products for sustainability: Innovations with multiples upgrade cycles.
Keywords:
Sustainable innovation, Upgrades, PSS, Remanufacturing

1 CONTEXT

Our society is increasingly concerned by environmental issues. The accelerating rhythm of products renewal causes accelerated exploitation of materials and energy. Today, with an annual consumption of raw materials of approximately 60 billion tons [1], the world population consumes about 50% more natural resources than 30 years ago [2]. In OECD countries, the domestic waste stream has increased by 40% in volume between 1980 and 1997 [3].

These current patterns of consumption and mass production are no longer compatible with sustainable development, a development that meets the needs of present generations without compromising the ability of future generations to meet their own needs [4]. To remedy this, it is necessary to imagine new paradigms of production / consumption, such as the "post mass production" [5] or the “parsimony” paradigm [6].

1.1 Upgrading and Remanufacturing

In order to contribute to the rationalization of the use of materials some recent works focus on the management of different “end of life options” for a product (or parts of a product) [7-10]. There are three main different end-of-life strategies: reuse, remanufacturing and recycling.

Remanufacturing is “the process of restoring discarded products to useful life" [11] or "the process of returning a used product to at least Original Equipment Manufacturer performance specification and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent” [12]. In our past research works [13], a more pro-active and global approach of designing remanufacturable systems has been defined: the MacPMR methodology of designing remanufacturable systems (which consists of six tasks [14]). In this method, a remanufacturable system is characterised by several cycles of use, several “meetings” between the customer/user and the product improved step by step with the integration of upgrades [15]. An upgrade is defined as a functional enrichment brought to the product. These upgrades brought to the product, at each change of cycle, increase the attractiveness of a remanufacturable system for the customer. This added attractiveness, brought dynamically and in step with integrated upgrades, is an opportunity for facilitating the dissemination of the remanufacturing approach.

1.2 Upgrading and Lifetime of product

More generally, with these upgrades the lifetime of any system can be increased. Why? Because, it becomes possible to manage the two key reasons why users discard products [7]: (a) Physical Life Time (PLT) [lifetime related to reliability] “the time until a product breaks down” and (b) Value LifeTime (VLT) [lifetime related to the obsolescence] “the time until a product is disposed when its performance, functionality or appearance cannot satisfy customer’s needs any more, although the product itself might work well.” [7]. The concept of “Utility Value” (UV) which reflects the “whole time” when the product has value [16] is similar: it depends both on “physical causes”, and “value causes”. The integration of upgrades can be made by a distributor/retailer, by a technician at home, by user (in “plug-and-play” way), etc., and not necessarily with remanufacturing operations. Then the reliability problems could be managed with the upgraded modules (when upgraded modules and no reliable modules are the same) or with a specific maintenance agreement. So upgrading is a way to increase the lifetime of any system. And delaying the replacement of a product is a strategy for rationalizing materials.

1.3 Upgrading and PSS

Another way for rationalizing materials is the dematerialization principle. Considering multiple cycles with integration of upgrades implies “upgradability services” and these added services could conduct manufacturers to switch offering more services, more precisely “Product-Service Systems” (PSS): “A product-service system is a system of

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

products, services, networks of actors and supporting infrastructure that continuously strives to be competitive, satisfy customers' needs and have a lower environmental impact than traditional business models" [17]. Three types of PSS are defined related on the share of services in these new offers [18]: product-oriented PSS, use-oriented PSS and result-oriented PSS. Increasing the rate of the product use by the servicizing of the offer represents another strategy for rationalizing materials. But it's hard to propose new service with added value: it's one of the reasons why PSS has difficult to generalize.

Aren't the upgrades a new potential to sell "addictive" services? Indeed, the integration of upgrades (functional enrichments brought to the product) could increase the attractiveness of a system for customers, step by step during its life. Therefore « upgradability services » is an opportunity for industrial companies who want to switch to offers with more services, and for the dissemination of PSS.

More generally, upgrading is an opportunity for the diffusion of sustainable innovation rationalizing materials, related to three points-of-view:

- end-of-life management point-of-view (dissemination of remanufacturing)
- extended lifetime point-of-view
- servicialization point-of-view (dissemination of PSS)

In this context, the issue of the need of product upgradability is very important and earns to be treated. That's why after presenting the upgrading opportunities for rationalizing materials in section 1, hypotheses to measure the real need of product upgradability are developed (section 2). This study is based on an important survey completed by a qualitative approach (section 3). The results which show the need of product upgradability are presented in section 4. Conclusions are discussed in section 5.

2 ISSUES

In marketing, there is a vast literature on how to sell products, the reasons for purchase, the satisfaction or the segmentation of customers. But very few papers explain the motivations and disincentives influencing the replacement decision.

The motivations influencing the replacement decision can be distributed in three categories [19]: product desired characteristics, situational influences, consumer characteristics. The parameters of product perception can be ordered in two dimensions: hedonic and utilitarian [20]. satisfaction drives fidelity [21]. Finally, three types of disincentives to repair a product are identified: financial cost/ temporal cost / risk [22].

In disincentives influencing the replacement decision, seven criteria for consumer-product attachment are identified: memories, self-identity, utility, life vision, enjoyment, market value, and reliability. Only the criterion "Memories" is positively related to the degree of consumer-product attachment [23]. A psychological cost, defined as the feeling of waste, has been identified [24].

An exploratory study has been done on the household products recently replaced by some people. This study was based on qualitative (45 persons) and quantitative (90 persons) questionnaires. The goal was to understand better (1) the reasons which motivate product replacement decision, (2) the reasons which curb product replacement decision and (3) the motivations and disincentives to repair. The results are presented in the table below (Figure 1)

. Main Motivations for Product replacement	
The replaced device no longer fulfilled its main function	reason cited spontaneously by 43.2% of respondents; importance in the decision = 5.7 /7
Willingness of more performance	43,2% ; imp. = 5,4 /7
Willingness of more Options	37,8% ; imp. = 5,3 /7
Willingness of more convenience	35% ; imp. = 5 /7
Because of Visual degradation	18,9% ; imp. = 3,7 /7
. Main brakes for Product replacement	
Price of the new device	64,9% ; imp. = 5,1 /7
Attachment to the old device	18,9% ; imp. = 3,3 /7
. Main Motivations to repair	
Low cost reparation	24,3%
Ecological motivation	16,2%
. Main brakes to repair	
Too expensive/value of device	37,8%
Uncertainty on the quality and the result	21,6%
Repairer hard to find	16,2%

Figure 1: Exploratory study results.

In this study on the recent replacement of a small appliance, two products are more frequent: vacuum cleaner & coffee machine. Even if there are some differences in the results between the different household products, this survey shows the following trends:

• 1. Disincentives for product replacement and motivations and disincentives to repair are mainly related to the price (of the product or the reparation).

• 2. Some devices that still work well are disposed (only 43% have a problem of main function).

From these results, the issue of replacement of products can be focused on the reasons why some devices that still work well are disposed. We make four hypotheses on the causes of product replacement which could also represent potentials in the future for the upgradability of products:

- H1- Upgradability concept requires a potential of disposed devices which still works.

When the device still works:

- H2- Upgradability concept requires a need for adaptability of product towards user needs: it is distinguished changing situation in the user's life (moving, animal adoption ...), weakening performance (declining primary function) and problems including reliability.
- H3- Upgradability concept requires a need for adaptability of product versus the competition.
- H4- Upgradability concept is consistent with an accumulation of problems.

3 RESEARCH METHODOLOGY

The original positioning of our article is that we don't want to add another theoretical paper but a concrete study with multi-country (France, Germany, Spain) point-of-views on a specific type of product, the electrical household devices.

To validate the need for upgradable products, two types of study have been conducted:

- a large quantitative survey related to the four hypotheses to quantify the product replacement causes
- a qualitative study (based on focus group) related to the hypothesis 3 to validate the "versatility" of consumers faced with the introduction of innovations.

3.1 Questionnaires

The first study is based on a quantitative survey as large as possible on the replacement causes based on 480 questionnaires of 50 items (Figure 2). This survey focuses on two specific products: the vacuum cleaner and the expresso machine, respectively a "drudgery" and "pleasure" device. To consider the context of purchase, this study was conducted in two types of retailers (supermarkets and specialized stores) and in three countries with different consumption habits (France, Germany, and Spain). The questionnaires were administered to people in real situation of product replacement.

	Supermarkets	Vacuum Cleaner	40 questionnaires
		Expresso Machine	40 questionnaires
	Specialized stores	Vacuum Cleaner	40 questionnaires
		Expresso Machine	40 questionnaires
	Supermarkets	Vacuum Cleaner	40 questionnaires
		Expresso Machine	40 questionnaires
	Specialized stores	Vacuum Cleaner	40 questionnaires
		Expresso Machine	40 questionnaires
	Supermarkets	Vacuum Cleaner	40 questionnaires
		Expresso Machine	40 questionnaires
	Specialized stores	Vacuum Cleaner	40 questionnaires
		Expresso Machine	40 questionnaires

Figure 2: The structure of the quantitative study.

The questionnaire is structured as follows:

- Set 1: questions around the replaced product (purchase, use, disposal)
- Set 2: questions about technical problems of the replaced product which push for its replacement
- Set 3: questions about the new features proposed by the market which encourage to purchase a new product
- Set 4: questions about the consumer and his life contributing to the product change

The goal is to distinguish different categories of behavior, by comparing these fields of questions and responses on the four hypotheses.

3.2 Focus Groups

This quantitative study was supplemented by a qualitative approach on a vacuum cleaner, based on a series of focus groups to trace the evolution of consumer choice criteria related on their experiences and knowledge of the new products. The goal is to better understand why people change products even if they still work perfectly.

In a first step, the participants imagine a list of innovations they want to integrate in the future product and they individually hierarchize them.

In a second step, 11 specific innovations illustrated by the Figure 3 are presented to the group. Then, each participant hierarchizes the innovations desired again, including the list of innovations imagined by the group and the 11 innovations proposed.

The last step consists in a comparison of the innovations chosen the two times, and their ranking. The "versatility" of consumers about the innovations desired depends on the variance of the results.

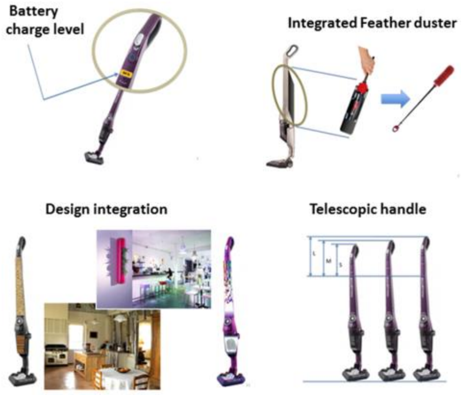


Figure 3 : Four innovations among the 11 proposed to the group.

4 EXPERIMENT AND RESULTS

4.1 Results of the quantitative survey

The analysis of the first results of the survey is presented below. In a first part, a comparison between the studies related to the vacuum cleaner and the expresso machine is proposed. In a second part, the comparison focus on the differences between the results obtained in France and in Germany (the survey in Spain is not completed) for vacuum cleaner, to show the importance of the cultural context.

4.1.1. Comparison between Vacuum Cleaner and Expresso Machine

For the vacuum cleaner and the expresso machine, more of 50% of products are disposed whereas they still work (Figure 4). This result confirms the potential for upgrading identified in the exploratory study: not all products are discarded because they are out of service (hypothesis 1), and so functional improvements could respond to these dissatisfactions in order to extend the lifetime of products.

For the expresso machine, classified more like a "pleasure" product than vacuum cleaner, more products are discarded even if they still work.

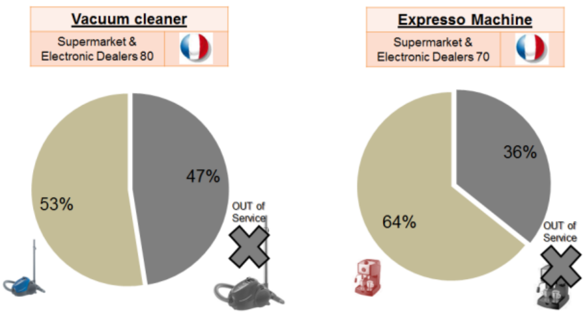


Figure 4: Hypothesis 1 - vacuum cleaner vs. expresso machine.

When the device still works, "the reasons related to adaptability or technical problems of the old device which push for its replacement" and "the reasons related to new features proposed by the market which encourage purchasing a new product" appear with a certain importance (hypotheses 2 & 3 - Figure 5). Upgrades could satisfy these two types of replacement causes. For the expresso machine, it seems that the reasons related on the benefits' promises of the new products are the majority. It's not the case for vacuum cleaner.

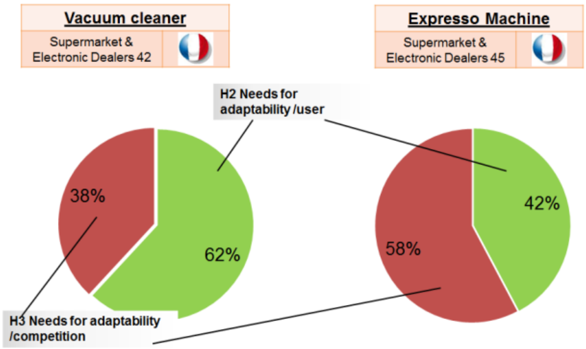


Figure 5: H2 & H3 - vacuum cleaner vs. expresso machine.

Focusing in the reasons related to adaptability or technical problems of the old device which push for its replacement (hypothesis 2), the problems including reliability are more prevalent than two others causes (Figure 6). A weakened performance on the main function represents only 11%. The share of the changing situation in the user's life (moving, animal adoption ...) is more important for vacuum cleaner.

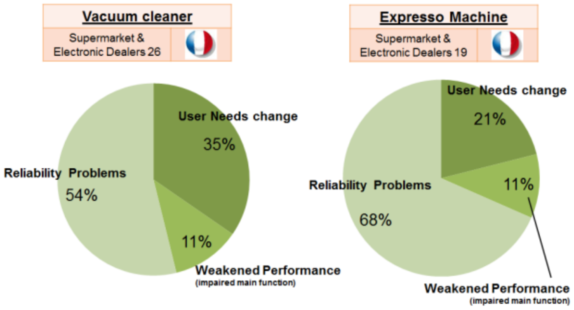


Figure 6: Focus on hypothesis 2 - vacuum cleaner vs. expresso Machine.

The Figure 7 shows the importance of problems accumulation related to: problem of suction (vacuum cleaner)/coffee quality (expresso machine), accessories problems, reliability problems, discomfort of use, handling problems, and maintenance problems. The concept of integrated functional improvements seems a good solution to correct dissatisfactions at the earliest date (hypothesis 4). For the expresso machine, the accumulation of problems is less important: the major cause identified is the quality of the delivered coffee. In fact, it's a product for "pleasure" and requiring few handling actions (it's a "press-button box"). So, the focus is on the quality of the delivered coffee. Consumers have a more hedonic approach. The upgrade concept is interesting for the coffee quality to follow the technological and "coffee fashion" changes, notably if you consider the possibility of different modules or accessories.

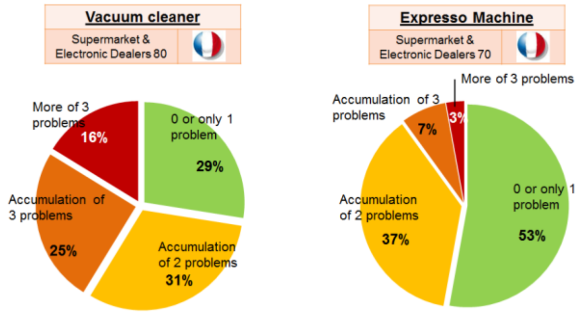


Figure 7: H4 - vacuum cleaner vs. expresso Machine.

4.1.2. Comparison between France and Germany (Vacuum cleaner)

The comparison between the results obtained in France and in Germany (the survey in Spain in not completed) shows a bigger share of disposed devices still working in Germany than in France (hypothesis 1 - Figure 8). The share of the reasons related to new features proposed by the market which encourage purchasing a new product are more important too (hypotheses 2 & 3 - Figure 9). German consumers seem to buy more expensive devices and to be more demanding than French consumers. Maybe that's why they have less problems of reliability (Figure 17) while they verbalize more problems (hypothesis 4 - Figure 11). The importance of the share of a weakened performance on the main function could be explained by the fact that the North European countries have more carpeting (Figure 10). The results are sensibly different but the four hypotheses on the need for product upgradability are validated too.

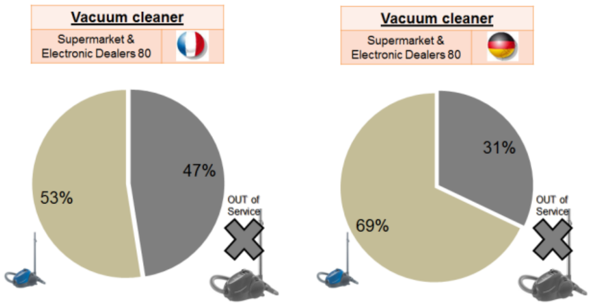


Figure 8: H1 – France vs. Germany.

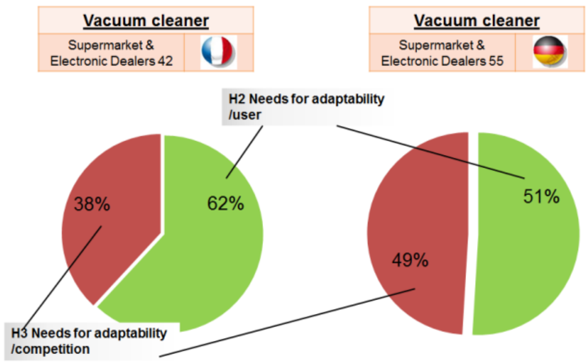


Figure 9: H2 & H3 – France vs. Germany.

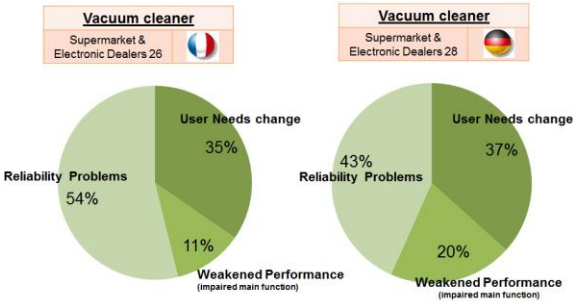


Figure 10: Focus on H2 - France vs. Germany.

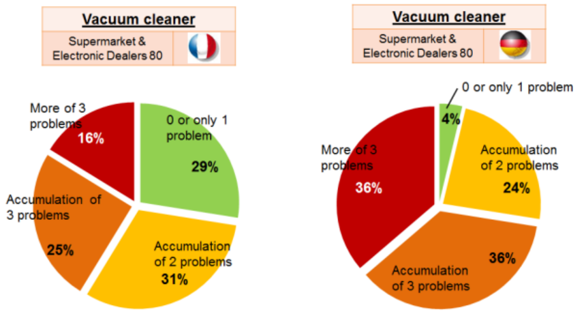


Figure 11: H4 - France vs. Germany.

4.2 Results of the Focus Groups

To complete the survey results, particularly on the Hypothesis 3, two focus groups on a vacuum cleaner have been organized to trace the evolution of consumer choice criteria related on their experiences and knowledge of the products. For confidential reasons, results are presented in term of "anonymous innovations".

From the first focus group (six persons), the results (Figure 12) show a strong variance between the two parts of the experiment. Only six innovations verbalized by the group are formulated twice (marked in yellow and green color) and only two at the same ranking level (marked in green color). The second part of this table shows that 11/18 innovations desired come from the 11 innovations proposed (see Figure 3).

From the second focus group (five persons), the results (Figure 13) show only two innovations formulated twice and none at the same ranking level. 12/15 innovations in the second part come from the 11 innovations proposed.

		hierarchy of evolutions verbalized by the group		hierarchy of evolutions after the presentation of innovations proposed
person 1	1	innovation n°4	1	innovation n°1
	2	innovation °1	2	innovation proposed n°3
	3	innovation n°2	3	innovation proposed n°4
person 2	1	innovation n°6	1	innovation proposed n°2
	2	innovation n°5	2	innovation proposed n°5
	3	innovation n°3	3	innovation n°3
person 3	1	innovation n°3	1	innovation n°1
	2	innovation n°4	2	innovation proposed n°6
	3	innovation n°1	3	innovation proposed n°2
person 4	1	innovation n°3	1	innovation proposed n°1
	2	innovation n°7	2	innovation proposed n°7
	3	innovation n°8	3	innovation n°3
person 5	1	innovation n°5	1	innovation n°1
	2	innovation n°3	2	innovation n°3
	3	innovation n°1	3	innovation proposed n°1
person 6	1	innovation n°2	1	innovation proposed n°8
	2	innovation n°3	2	innovation proposed n°2
	3	innovation n°9	3	innovation n°1

Figure 12: Results of the focus group 1.

		hierarchy of evolutions verbalized by the group		hierarchy of evolutions after the presentation of innovations proposed
person 1	1	innovation n°6	1	innovation proposed n°9
	2	innovation n°5	2	innovation proposed n°3
	3	innovation n°1	3	innovation proposed n°1
person 2	1	innovation n°6	1	innovation proposed n°3
	2	innovation n°10	2	innovation proposed n°10
	3	innovation n°5	3	innovation n°10
person 3	1	innovation n°5	1	innovation n°10
	2	innovation n°10	2	innovation proposed n°8
	3	innovation n°1	3	innovation proposed n°1
person 4	1	innovation n°11	1	innovation n°2
	2	innovation n°1	2	innovation proposed n°1
	3	innovation n°12	3	innovation proposed n°6
person 5	1	innovation n°5	1	innovation proposed n°10
	2	innovation n°6	2	innovation proposed n°9
	3	innovation n°12	3	innovation proposed n°3

Figure 13: Results of the focus group 2.

These results show the "versatility" of consumer choice criteria related on their experiences and knowledge of the potential innovations. For certain persons, these new features proposed by the market are sufficient to encourage them purchasing a new product. This population is included in the share entitled "need for adaptability of product /competition" (hypothesis 3).

5 CONCLUSIONS

In this paper, the necessity to consider innovations with multiples upgrade cycles for rationalizing of materials is showed.

The first results of the survey related to the replacement of the vacuum cleaner and the expresso machine show that more of 50% of products are disposed whereas they still work (hypothesis 1 validated). In this park of discarded devices which still works, the replacement reasons concern both the "adaptability or technical problems of the old device which push for its replacement" (hypothesis 2 validated) and the "new features proposed by the market which encourage purchasing a new product" (hypothesis 3 validated). This survey also shows the importance of problems accumulation and/or the variety of these problems (hypothesis 4 validated). The need of product upgradability is validated.

More precisely, for the expresso machine, classified as "pleasurable product" (vacuum cleaner is more identified "house work"), and in the cultural context of Germany, the share of product replacement due to the "new features proposed by the market which encourage purchasing a new product" are more important. The results of two focus groups confirm the "versatility" of consumers in front of the potential innovations proposed to them, which can be sufficient to encourage purchasing a new product. These last results show different determinants (type of product, cultural and competition context, consumer) to define the upgrade integration strategy of an upgradable system. Some issue arise: How many upgrades must be integrated? What types of upgrades? What upgrade integration rhythm?

Faced with the changes in competitors and the evolving needs of customers, the product is currently designed as a too static artefact. We claim the necessity of a new sort of "evolutionary" products able to adapt themselves gradually to the evolving requirements of users by upgrades integration while improving radically the environmental performance on all life cycles (see Figure 14): compared to a conventional product which is changed every six years, an upgradable product with functional enrichment brought more regularly allows an important material consumption reduction. With the possibility to upgrade the product, the lifetime of the product may be longer, and new possibilities to provide more services that provide value to the customer and money to the company appear.

Faced with these new issues (rhythm of upgrade integration, business model changes, improvement of environmental impact on several cycles …), this paper shows the necessity to develop a new design methodology (Design for upgradecycling).

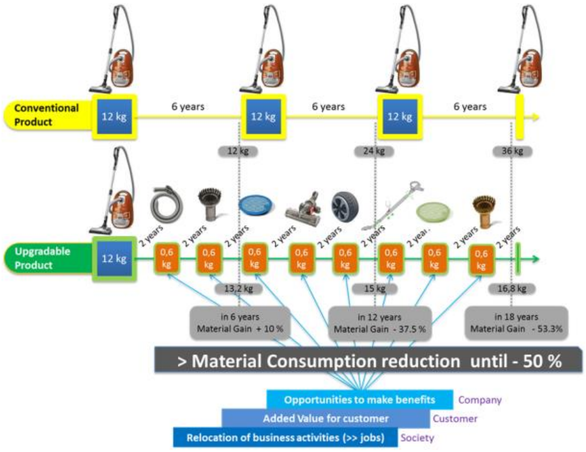


Figure 14: Sustainable innovation with upgrade cycles.

6 ACKNOWLEDGMENTS

The “Design for upgradecycling” project (IDCyclUM) is an industrial research project (40 months) financially supported by the French research agency. The consortium is composed of seven partners: the laboratories LISMMA, G-SCOP, COSTECH, GAEL, IWF (Germany) and industrial companies ROWENTA and NEOPOST.

7 REFERENCES

[1] SERI Research center, « Amis de la Terre » Europe, 2009, Report : Overconsumption? Our use of the world´s natural resources, p. 3.

[2] Commissariat général au Développement durable, 2010: « Le point sur le recyclage et le réemploi, une économie de ressources naturelles », p. 1.

[3] Report from the Commission to the Council and the European Parliament on implementation of the community waste legislation for the period 2001-2003, 2006, COM(2006) 406 final, Brussels,.

[4] World Commission on Environment and Development, 1987. Our common future. Oxford, UK: Oxford University Press.

[5] Umeda, Y., Nonomura, A. et Tomiyama, T., 2000, Study on life-cycle design for the post mass production paradigm. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 14(2):149–161,.

[6] Cucuzzella C., 2009, The limits of current evaluation methods in a context of sustainable design: prudence as a new framework, International Journal of Design Engineering, Volume 2 - Issue 3.

[7] Umeda Y., Daimon T. and Kondoh S., 2007, Life cycle option selection based on the difference of value and physical lifetimes for life cycle design, ICED, Paris.

[8] Rose C., Ishii K. and Stevels A., 2002, Influencing Design to Improve Product End-of-life Stage, Research in Engineering Design. 13, pp. 83–93.

[9] Xing, K., Abhary, K., & Luong, L., 2003, IREDA: An Integrated Methodology for Product Recyclability and End-of-life Design. The Journal of Sustainable Product Design, 3(3), 149-171.

[10] Takeuchi, S., & Saitou, K., 2006, Design for optimal end-of-life scenario via product-embedded disassembly. DETC2006 ASME, 10-13 septembre.

[11] Lund, R.T., 1996, The Remanufacturing Industry: Hidden Giant. Boston. Argonne National Lab. study.

[12] Ijomah, W.L., 2002, A model-based definition of the generic remanufacturing business process. University of Plymouth.

[13] Tchertchian N., Millet D., 2011, Design for Remanufacturing: What performances can be expected?, International Journal of Environmental Technology and Management.

[14] Tchertchian N., Millet D. and El Korchi A., 2010, A method helping to define eco-innovative systems (Product Architecture + Reverse Supply Chain structure + Use Cycles Scenario) In LCE 2010, Hefei - China.

[15] Pialot O., Millet D., Tchertchian N., 2012, How to explore scenarios of multiple upgrade cycles for sustainable product innovation: the “Upgrade Cycle Explorer” tool, Journal of Cleaner Production , Vol. 22.

[16] Kondoh S., Mishima N., Masui K. and Matsumoto M., 2009, Total performance design of product life cycle considering future uncertainties, International Journal of Design Engineering.

[17] Mont O., 2002, Clarifying the Concept of Product-Service System. Journal of Cleaner Production.

[18] Maussang, N., 2008, Méthodologie de conception pour les systèmes Produits-Services, Thèse de doctorat de l'INP Grenoble, Novembre.

[19] Van Nes, N., Cramer, J., 2006, Design strategies for the lifetime optimisation of products, The journal of Sustainable Product Design, Springer.

[20] Voss KE, Spangenberg ER, Grohmann B, 2003, Measuring the hedonic and utilitarian dimensions of consumer attitude. Journal of Marking Research.

[21] Goderis, J.-P., 1998, “Barrier marketing: from customer satisfaction to customer loyalty”. CEMS Business Review. 2 (4), 285-294.

[22] Mc Cullough, 2010, Consumer Discount Rates and the decision to repair or replace a durable product: a sustainable consumption issue, Journal of Economic Issues, XLIV, 1, 183-204.

[23] Schifferstein, H.N.J., Mugge, R., & Hekkert, P., 2004, Designing consumer-product attachment, in Design and Emotion: The Experience of Everyday Things. Taylor & Francis, London, pp. 327-331.

[24] Okada, 2001, Trade-Ins, mental accounting, and product replacement decisions, Journal of Consumer Research, 27, 433-446.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

3.3 Material efficiency in companies of the manufacturing industry: classification of measures

S. Fischer [1]
[1] Wuppertal Institute for Climate, Environment, Energy, Germany

Abstract
Improving material efficiency in the manufacturing industry is a sustainability imperative for companies due to economic and environmental advantages such as the reduction of material costs and resource use. Innovative solutions in terms of material efficiency measures are diverse and widespread. As a systematic assessment of efficiency approaches and their effects are likely to support dissemination and deployment, this paper aims to develop an approach that helps to classify material efficiency measures. The classification approach presents different dimensions and properties of material efficiency measures based on a literature analysis regarding existing classification approaches as well as on work that has been conducted for the Eco-Innovation Observatory. The classification has been designed as basis for an empirical impact assessment of material efficiency measures based on a data sample that stems from the German Material Efficiency Agency.
Keywords:
Classification; Material Efficiency Measure; Sustainable Manufacturing

1 INTRODUCTION

Material engineering and processing companies are facing change. Growing constraints regarding material availability and increasing raw material prices are increasingly anticipated as entrepreneurial risks requiring preventive adaption strategies [1] [2]. At the same time, new business chances in terms of revenue growth, comparative cost advantages, an improved risk management and a better reputation appear to be tangible for those companies that manage those challenges pro-actively [3]. Pro-active businesses would not only be in the favourable position to realise these potentials, but also to “change the rules of the game” [4].

One opportunity for companies to meet the changing framework conditions is the implementation of measures that lead to an improved material efficiency and thus to a reduced use of material resources. Recently, data from case studies from the Germany Material Efficiency Agency (demea)—which offers support to consult small and medium sized enterprises regarding the implementation of material efficiency measures (MEMs)—were analysed by a number of studies and projects [5] [6] [7]. It was revealed that implementing simple and low-cost MEMs can lead to savings of around € 200,000 per company and year, corresponding to 2 % of the yearly company turnover and facing one-off investments of around € 130,000.

Nonetheless, the actual implementation in business leaves much to be desired—only one in seven of all companies and one in four innovating companies in the EU-27 are introducing those kinds of innovation that lead to a material use reduction [6]. Amongst others, the lack of entrepreneurial action can be traced back to barriers (e.g. uncertainties concerning the return on investment). In order to accelerate the application of MEMs, decision makers in business need to be better informed about MEMs, their costs and benefits. To this end, an improved understanding about the range of different MEMs would be useful.

The present paper addresses this subject. Based on the analysis of scientific articles, studies and other publications, it will present a possible classification approach of MEMs. The developed approach will be the future basis for an in-depth analysis of the demea case studies.

2 LITERATURE ANALYSIS

2.1 Definitions

The concept of efficiency compares the inputs of a system with the outputs of that system. Regarding material efficiency on a corporate level, the inputs of the system are physical resources that go into a production process with the output of produced goods (products and services), which have an economic value. The less material input is needed to generate the same amount of output (or the more output is generated with the same amount of input), the more efficient the system is. Correspondingly, a MEM would be an entrepreneurial action that has the aim to reduce the input of materials while the same economic output is generated with regard to the production of goods.

Material efficiency is closely related to the concept of resource efficiency, with the difference being that they have different system boundaries. The material efficiency concept focuses on one stage of a resource’s life-cycle, in contrast, the concept of resource efficiency is more broad as it regards the efficiency of a resource’s extraction, its use and resulting environmental impacts over all life-cycle stages [8]. This paper focuses on sustainable manufacturing und thus on the manufacturing phase, consequently, the efficiency term of this paper refers to the material efficiency concept.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2.2 Method

A plethora of scientific knowledge regarding the subject of material efficiency has been generated over the past few years. In order to analyse the diffusion of the *classification of material efficiency measures in companies of the manufacturing industry* in the scientific discussion, a keyword search was conducted. As part of the search, the publication databases Web of Knowledge, Scirus, BASE, Google Scholar and ScienceDirect were scanned for publications that contain the following keywords and/or combinations of them (e.g. *material, efficiency, measure, categorisation*), as far as possible within the title and/or the full text:

- *material* OR *resource*,
- *efficiency* OR *productivity*,
- *measure* OR *strategy*,
- *classification* OR *categorisation*,
- *manufacturing*.

More than 20,000 documents (including redundant hits as well within as across databases) including the above mentioned keywords and/or combinations were found in the five databases. However, hits were screened only until a number of 150 entries per search query, so that around 4,000 documents were screened very roughly for a thematic relevance to the research question of this paper. As a result, around four dozen reviewed articles were considered to be the most promising and were used for a deeper analysis. Additionally, cross-references with further subjects such as (eco-)innovation, (cleaner) production, (sustainable) manufacturing etc. and links to further publications such as other journal articles, books and book chapters, conference contributions, project reports etc. were researched and included into the literature analysis as well.

3 CLASSIFICATION OF MATERIAL EFFICIENCY MEASURES

3.1 Terminology

The following approach including the ensuing terms will be used for the classification of MEMs: A MEM can be classified regarding different *dimensions*. Each dimension is described by a bundle of *properties*, of which only one property can be valid per dimension. It is possible to specify properties on further levels by introducing sub-properties. The collection of all valid properties across the different dimensions forms the *type* of the MEM. Distinguishing MEMs by their types, in terms of valid properties across the different dimensions, shall constitute this paper's approach of how to classify MEMs.

3.2 Classification approaches in the literature

In the course of the literature analysis, general insight regarding classification approaches of MEMs in scientific literature was gained.

Due to the fact that there are a lot of different terms when it comes to describing the material efficiency concept, the search for classification approaches of material efficiency measures was aggravated. In order to have a higher or better hit quota, additional expressions such as *resource efficiency,* etc. were included into the search. It is however evident that this choice was not able to cover the whole range of possible terms describing the same phenomenon (e.g. expressions such as *material* or *resource use* and *savings* or *benefits* would have been possible, too). There are also a number of synonyms for *measure* and *strategy* (e.g. *innovation*, *practice*, *action* or *opportunity*) and *classification* and *categorisation* (e.g. *typology*, *group*, *set* or *characteristic*).

A further factor making searches more challenging is the importance of the classification of MEMs for the respective publication. In most of the cases, the classification approach is more a methodological step on the way to analyse a specific research question than the essence of the scientific publication itself. As the classification happened more incidentally, the identification of classification approaches in the literature is possible in limited form only (e.g. as it is not necessarily listed in the publication title, however the titles were used for the rough screening regarding the thematic relevance of the publication).

Only a small number of the publications considered as promising developed a general approach of how to classify MEMs (e.g. in [5] [9] [10]). For the most part, the publications dealt with only one thematic area and therefore with only one classification dimension and its different properties (e.g. green technologies in [11] [12] [13]).

Furthermore, there are publications about MEMs that presented a bundle of common and concrete MEMs, however failed to introduce a general classification (e.g. in [14] [15] [16]).

3.3 Own classification approach

As a result of the literature analysis, the following thirteen dimensions and their properties to classify MEMs were identified. Some of the dimensions were further specified on a second- and third-tier level (see **Table 1**). The choice of dimensions and properties is not understood to be complete and exclusive—it is rather a first approach of how a MEM classification could look like.

General nature (dimension 1)

The general nature of a MEM gives an answer to the question of the pursued superior strategy: Is it a business model decision, a technical option, an organisational change or a personnel development measure? These four properties are the result of different approaches found in the literature. Other perspectives for the general nature of a MEM would have also been possible; for the most part they are, however, reflected in the following dimensions.

Due to the wide scope of the general nature dimension, the four properties are further specified on a second-tier level. Whereas the properties for the business model are based on a single and pertinent source [17], the technical material efficiency properties have been compiled on the basis of several approaches from diverse literature findings. Technical material efficiency changes can target a company's infrastructure, its product design, manufacturing method, production planning and production process, the sphere of manufacturing and it can be another technical strategy, too. This classification, however, is still too rough. Therefore a third-tier level has been introduced that specifies the technical material efficiency strategies:

- The infrastructure dimension distinguishes between changes regarding technology, machines, tools and the building including other equipment. The technology dimension again is manifold and could be further specified, such as into environmental, optical, automation, information and communication, production, energy, material and building technology and nano- and biotechnology [18]. Again, the environmental technologies could be further specified to e.g. cleansing, cleaner process and clean technologies, etc. [11].

- The product design determines the material use of a product during its life-cycle phases to an enormous extent—80 % of the economic cost and environmental and social impacts are fixed through the product design [19]. There are a lot of opportunities to determine the material use already in the design phase [20] [21] [22]: changes in the product function (e.g. combined functions), durability, size, construction, choice of materials (e.g. use of secondary raw materials) and auxiliary materials and considering resource efficiency aspects during the phases of manufacturing, packaging, use, reuse (or remanufacturing or recycling) and final waste treatment.
- The decision for a certain manufacturing method can be the subject of a MEM. Decisions regarding the following manufacturing method properties are possible: material flow structure (e.g. convergent material flows), cross linking of manufacturing steps (e.g. circular material flow), degree of repetition (e.g. serial production), physical arrangement of manufacturing steps (e.g. workshop production) and other technical determinants (e.g. changing from a chemical to a biological process).
- Whereas changes regarding infrastructure, product design, and manufacturing method are of a more long-term nature, modifications concerning the production planning are characterised by mid- and short-term actions. Setting the production program (e.g. volume of products to be produced in a certain period), materials management (e.g. determination of material requirement) and actual operation scheduling (e.g. capacity and sequence planning) is also part of technical material efficiency strategies.
- In connection with the production planning the actual physical production process offers further possibilities to influence material efficiency on a technical basis—in terms of production control (e.g. concrete job approval), machine setting (e.g. technical adjustments) and the operating of machines (e.g. optimised handling).
- The sphere of manufacturing also offers material efficiency opportunities in terms of actions regarding the workplace design [5], maintenance and cleaning, storage and cleaning and packaging.
- In addition to the named sub-properties of the technical material efficiency dimension, superior technical strategies that target quality management (e.g. implementation of a company wide monitoring, controlling and benchmarking system), use of information technology (e.g. new software) and a material flow management (e.g. in order to implement in-house and closed-loop material flows) have been introduced as final classification properties for technical MEMs.

Life-cycle stage (dimension 2)

The MEM can target different life-cycle stages: the phase of the resource extraction, manufacturing, transport, etc. The properties describing those phases have been taken from the supply chain operations reference model [23] and comprise the stages of plan, source, make, deliver and return.

The dimension of the planning level takes different time horizons into account. Planning decisions can be normative, strategic, tactical and operational [24] with decisions affecting the above listed technical material efficiency strategies (e.g. strategic decisions about product design, or tactical determination of the production program).

Corporate division (dimension 3)

The dimension of the corporate division comprises the properties management, corporate culture, human resources, research and development, product design, marketing, controlling, procurement, manufacturing, maintenance and cleaning, storage and logistics and packaging. These could be assigned to the life-cycle stages, too (e.g. research and development to planning or manufacturing to making)—it is, however, interesting to learn which corporate division is able to influence the material efficiency performance of the enterprise.

Mechanism (dimension 4)

The idea regarding a mechanism dimension has been taken from a methodology of how to describe sustainable manufacturing tactics [25]. It depicts how the material efficiency effect takes place. The concrete properties were chosen in analogy with the waste hierarchy defined by the European Union [26] that differentiates between prevention, reuse, recycling, recovery and disposal (as the latter one is not relevant in terms of material efficiency improvements, it is not included in the properties of this dimension).

Material (dimension 5)

A MEM reduces the use of materials. The material dimension gives an overview of the saved material type. On the first-tier level the dimension is simply characterised by input and by output material. In accordance with a guideline of how to calculate the material input per service unit [27], on a second-tier level, the input material is further specified by abiotic and biotic raw materials, energy sources and carriers, water, air, components, models, auxiliary and operating materials. Accordingly, the output material is further specified by main and by-products, waste, emissions, waste water and exhaust air.

Degree of change (dimension 6)

MEMs lead to a change in the respective company. To which degree that change takes place gives occasion to introduce a further classification dimension. Commonly, it is distinguished between small and high degree changes—in terms of e.g. incremental and radical innovations [28] [29] [30]. In this paper the focus lies more on business-related incremental than society-related radical changes, therefore an approach [31] is chosen that focuses more on incremental changes. Modification, redesign, alternatives, and (with respect to radical and system changes) creation are the properties of the degree of change dimension.

Degree of novelty (dimension 7)

Complementary to the degree of change, a differentiation regarding the degree of the MEM's novelty is possible. As the definition of novelty is not possible per se [32], a framework for comparison is necessary: Is the measure just new to the firm, but already implemented by other companies in the same market segment? Is it new to the market or new to the world? The answers to these questions are the properties chosen for the classification approach of this paper.

Directness of effect (dimension 8)

Whether the material reduction effect of a MEM occurs immediately after the implementation or is delayed by a certain amount of time or whether the effect occurs at the place where the measure has been implemented or further downstream is a further classification dimension. It is differentiated between direct and indirect effects [33] [34].

Measurability (dimension 9)

Related with the question regarding the directness of effect is the measurability of an effect. Effects can be measured on a quantitative (e.g. saved material amount through changed machine adjustments) or a qualitative basis (e.g. better housekeeping through awareness raising measures).

Risk structure (dimension 10)

The introduction of MEMs can pose a path dependence risk to the company in terms of the ecological, economic and technical reversibility [35]. These features could be taken as properties for the dimension of risk structure. However, a MEM could be all three—difficult to be reversed in ecological, economic and technical terms. Therefore, a differentiation between a low, middle and high risk, based on the different reversibility aspects are chosen as properties in order to describe the risk structure of a MEM.

Technical education (dimension 11)

The technical education that is needed in order to introduce and to implement the MEM is a further classification dimension of MEMs. The chosen properties for that dimension differentiate between maintenance personnel, engineering personnel and technology expert [9].

Implementation time (dimension 12)

The time that a measure needs to be implemented is a further dimension of MEM classification. The implementation time is short when it is below six months; it is medium when it takes between six months and one year. In case it takes longer than one year, the implementation time is long.

Measure duration (dimension 13)

The duration of the MEM constitutes another classification dimension. In case it has a five year life expectancy it is a short-term measure. With a lifetime between 5 and 20 years it is a medium-term and more than 20 years it is a long-term measure [9].

Table 1: Classification of material efficiency measures (first-, second- and third-tier level)

Dimensions		**Properties**				
1	**General nature**	business model	technical material efficiency	organisation	personnel development	
1.1	**Business model**	value proposition	target customer	distribution channel	relationship	value configuration
		core competency	partner network	cost structure	revenue model	
1.2	**Technical material efficiency**	infrastructure	product design	manufacturing method	production planning	production process
		sphere of manufacturing	other technical strategy			
1.2.1	**Infrastructure**	technology	machine	tool	building and equipment	
1.2.2	**Product design**	function	durability	size	construction	material choice
		auxiliary materials	manufacturing	package	use	reuse
		waste treatment				
1.2.3	**Manufacturing method**	material flow structure	cross linking of manufacturing steps	degree of repetition	physical arrangement of manufacturing steps	technical determinants
1.2.4	**Production planning**	production program	materials management	process organisation		
1.2.5	**Production process**	production control	machine setting	operating of machines		
1.2.6	**Manufacturing sphere**	workplace design	maintenance and cleaning	storage and logistics	packaging	
1.2.7	**Other technical strategy**	quality management	IT assistance	material flow management		
1.3	**Personnel development**	awareness raising and good housekeeping	position creation			

2	**Life-cycle stage**	plan	source	make	deliver	return
2.1	**Planning level**	normative	strategic	tactical	operational	
3	**Corporate division**	management	corporate culture	human resources	research and development	product design
		marketing	controlling	procurement	manufacturing	maintenance and cleaning
		storage and logistics	packaging			
4	**Mechanism**	prevention	reuse	recycling	recovery	
5	**Material**	input material	output material			
5.1	**Input material**	abiotic raw materials	biotic raw materials	energy sources / carriers	water	air
		components	modules	auxiliary materials	operating materials	
5.2	**Output material**	main products	by-products	waste	emissions	waste water
6	**Degree of change**	modification	redesign	alternatives	creation	
7	**Degree of novelty**	new to the firm	new to the market	new to the world		
8	**Directness of effect**	direct	indirect			
9	**Measurability**	quantitative	qualitative			
10	**Risk structure**	high risk	middle risk	low risk		
11	**Technical education**	maintenance personnel	engineering personnel	technology expert		
12	**Implementation time**	short (<6 months)	medium (6-12 months)	long (>1 year)		
13	**Measure duration**	short-term (<5 years)	medium-term (5-20 years)	long-term (>20 years)		

4 CONCLUDING REMARKS

Based on literature research, this paper has developed an approach of how to classify MEMs in companies of the manufacturing industry. The approach consists of thirteen dimensions that are specified by a number of properties (and where appropriate also on a second- and third-tier level), of which only one property per dimension is valid for a certain MEM. The collection of all valid properties regarding the thirteen dimensions forms the respective MEM type.

The approach does not claim to represent the entire reality, it is even highly likely that the dimensions and properties can be amended or refined. Changes in some other form could also be possible because defining distinct properties for dimensions that look from different perspectives on a similar issue cannot always happen without any overlap (e.g. packaging is a property of the dimensions product design, manufacturing sphere and corporate division).

Despite possible weaknesses, the developed classification approach could serve as the basis for a detailed analysis of case studies as conducted by the demea. MEM types shall be compared with each other in order to find patterns that allow deductions regarding MEM type-related material saving potentials (in physical and monetary terms), investment costs and payback times.

To give an example, measures in the demea cases comprise amongst others changes concerning the reduction of set-up times, changed temperature in the production process, use of filters, alternative coating method, re-use of dissolvent, improved definition of employee responsibilities, machinery cleaning, product size, use of IT in order to support production simulation and quality control of purchased commodities [36]. According to this paper's classification approach, they all target the technical material efficiency property within the general nature dimension. On a second- and third-tier level the MEMs are further specified by sub-properties such as process organisation (production planning), machine setting (production process), tool (infrastructure), technical determinants and material flow structure (manufacturing method), operating of machines (production process), maintenance and cleaning (manufacturing sphere), size (product design), IT assistance and quality management (other technical strategy). Identifying the properties of the remaining twelve dimensions and building the MEM types would be the next steps on the way to the classification of the given MEMs.

In order to accelerate the dissemination and deployment of MEMs in companies of the manufacturing industry, the classification of MEMs needs to take place on a larger scale combined with the deduction of MEM patterns and determination of the economic leverages and payback times.

5 REFERENCES

[1] KPMG, 2012, Expect the Unexpected: Building business value in a changing world.

[2] World Economic Forum, 2011, Global Risks 2011.

[3] WBCSD, 2010, Vision 2050: The new agenda for business.

[4] Sommer, A, 2012, Managing Green Business Model Transformations, Springer.

[5] Schmidt, M., Schneider, M., 2010, Kosteneinsparungen durch Ressourceneffizienz in produzierenden Unternehmen, Uwf, 18:153–164.

[6] EIO, 2012, Closing the eco-innovation gap: An economic opportunity for business, DG Environment.

[7] Greenovate! Europe, 2012, Guide to resource efficiency in manufacturing, Europe Innova.

[8] Abdul Rashid, S., Evans, S., Longhurst, P., 2008, A comparison of four sustainable manufacturing strategies, Int. J. Sustain. Eng., 1:214–229.

[9] Fleiter, T., Hirzel, S., Worrell, E., 2012, The characteristics of energy-efficiency measures – a neglected dimension. Energy Policy, 51:502–513.

[10] Allwood, J. M., Ashby, M. F., Gutowski, T. G., Worrell, E., 2011, Material efficiency: A white paper, Resour. Conserv. Recycl., 55:362–381.

[11] Kuehr, R., 2007, Environmental technologies – from misleading interpretations to an operational categorisation & definition, J. Clean. Prod., 15:1316–1320.

[12] Lang-Koetz, C., Pastewski, N., Rohn, H., 2010, Identifying New Technologies, Products and Strategies for Resource Efficiency, Chem. Eng. & Technol., 33/4:559–566.

[13] Ritthoff, M., Liedtke, C., Kaiser, C., 2007, Technologien zur Ressourceneffizienzsteigerung: Hot Spots und Ansatzpunkte, Wuppertal Institut.

[14] Barrett, J., Scott, K., 2012, Link between climate change mitigation and resource efficiency: A UK case study, Glob. Environ. Change, 22:299–307.

[15] Schröter, M., Lerch, C., Jäger, A., 2011, Materialeffizienz in der Produktion: Einsparpotenziale und Verbreitung von Konzepten zur Materialeinsparung im Verarbeitenden Gewerbe, Fraunhofer ISI.

[16] Ackroyd, J., Titmarsh, L., Coulter, B., Dombey, A., Phillips, P. S., 2006, Business excellence through resource efficiency (betre): East Sussex waste minimisation programme, Resour. Conserv. Recycl., 46:217–241.

[17] Osterwalder, A., Pigneur, Y., Tucci, C. L., 2005, Clarifying business models: Origins, present, and future of the concept, Commun. Assoc. Inf. Syst., 1-40.

[18] Rohn, H., Lettenmeier, M., Pastewski, N., 2011, Identification of Technologies, Products and Strategies with High Resource Efficiency Potential, in Int. Econ. Resour. Effic. (Bleischwitz, R., Welfens, P. J. J. & Zhang, Z.) 335–347, Physica.

[19] Tischner, U., Charter, M., 2001, Sustainable product design, in Sustain. Solutions (Charter, M. & Tischner, U.) 118–138, Greenleaf Publishing.

[20] Van Berkel, R., Willems, E., Lafleur, M., 1997, Development of an industrial ecology toolbox for the introduction of industrial ecology in enterprises, I. J. Clean. Prod., 5:11–25.

[21] Ji, Y., Jiao, R. J., Chen, L., Wu, C., 2013, Green modular design for material efficiency: a leader–follower joint optimization model, J. Clean. Prod., 41:187–201.

[22] Charter, M., Gray, C., 2008, Remanufacturing and product design, Int. J. Prod. Dev., 6:375–392.

[23] Francis, J., 2011, SCC and SCOR Overview.

[24] Dyckhoff, H., 2006, Produktionstheorie: Grundzüge industrieller Produktionswirtschaft, Springer.

[25] Despeisse, M., Ball, P. D., Evans, S., 2012, in Sustain. Manuf. (Seliger, G.) 9–16, Springer.

[26] The European Parliament and the Council of the European Union, 2008, DIRECTIVE 2008/98/EC on waste and repealing certain Directives.

[27] Ritthoff, M., Rohn, H., Liedtke, C., 2002, Calculating MIPS : resource productivity of products and services.

[28] Freeman, C., Perez, C., 1988, Structural Crises of Adjustment, Business Cycles and Investment Behaviour, in Tech. Change Econ. Theory (Dosi, G., Freeman, C., Nelson, R. R., Silverberg, G. & Soete, L.) 38–66, Pinter.

[29] Rennings, K., 2000, Redefining innovation — eco-innovation research and the contribution from ecological economics. Ecol. Econ., 32:319–332.

[30] Carrillo-Hermosilla, J., del Río, P., Könnölä, T., 2010, Diversity of eco-innovations: Reflections from selected case studies, J. Clean. Prod., 18:1073–1083.

[31] OECD, 2009, Sustainable Manufacturing and Eco-Innovation: Framework Practices and Measurement.

[32] Konrad, W., Nill, J., 2001, Innovationen für Nachhaltigkeit, IÖW.

[33] Fichter, K., Arnold, M., 2004, Nachhaltigkeitsinnovationen, Universität Oldenburg.

[34] Kristof, K., Welfens, M. J., Türk, V., Walliczek, K., 2007, Ressourceneffizienzsteigerungen durch organisatorische und institutionelle Innovationen, Wuppertal Institut.

[35] Paech, N., 2005, Nachhaltige Innovationen: Zur Gestaltung ambivalenter Prozesse des Wandels, in Jahrb. Ökologische Ökonomik 225–250, Metropolis.

[36] Fischer, S., O'Brien, M., 2012, Eco-innovation in Business: reducing cost and increasing profitability via Material Efficiency Measures, EIO.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

3.4 Process optimization of resources for packaged water factories in Nigeria

S. C. Nwanya, P. O. Onah, I. E. Onyia

Department of Mechanical Engineering, University of Nigeria, Nsukka , Nigeria

Abstract

Inaccessibility to drinking water is an intractable growing problem in developing countries such as Nigeria. This paper, presents the energy and manpower input resources needed to increase water accessibility and guarantee sustainable profitable operations. The work relied on detailed questionnaire administration for data collection from water packaging factories within Nsukka and Enugu Cities. The data were collated and Project Evaluation Review Technique (PERT) was used to determine the amount of energy needed. A profit profile was determined for both sachet and bottle water products. The gross energy sequestered by the packaging process is 87.8J for sachet water and 0.52 MJ for bottle water with average of 10 workforces. Also, optimal production rates of 1658 and 1551 were determined for sachet and bottle water, respectively at a profit of ₦ 291,428.29 per day. The results have significant implications for Nigeria's millennium development goals target for water in 2015.

Keywords:

Energy, optimization, packaged water, process resources

1.0 INTRODUCTION

People need access to a clean water supply for varied uses. Paradoxically, there is shortage of clean water as demand for it continues to grow across the globe at an alarming rate. With almost two – thirds of earth covered by water, it is difficult to understand how a shortage of clean water supply could exist. However, it does exist as only one percent of the water in the world is consumable without treatment [1]. Presently, 1.1 billion people in developing countries have inadequate access to water. The water crisis has also affected health matters of human beings and the cost associated with health spending, productivity losses and labour are greatest in poorest countries with sub-sahara Africa loss about 5 % of its GDP [2]. Since the aforementioned one percent cannot meet the world demand, people have decided on a set of potential interventions for increasing access to water supply.

Generally, two kinds of interventions exist, namely improved water supply technologies (household connections, public standpipe, borehole, and protected spring and rain water collections) and unimproved water supply technologies (unprotected well and spring, vendor provided water and tanker truck provision of water) [3].

Inaccessibility to improved drinking water supply technologies is more acute in rural areas than urban cities. The worsen water shortages in developing world if allowed to continue, the fall-out can reverse significantly progress towards achieving the MDG targets in 2015. As a result, there is need to optimize process factors that will encourage privately owned water enterprises (POWE) to embark on profitable packaging of borehole water through efficient input resource management. Although, government-owned public water utilities (GPWU) schemes used in the past could serve more people than borehole, the former is more expensive to build, maintain and its services are limited by bureaucracy and difficult terrain. Conversely, energy, material and labour are input process factors required for both schemes to function. This work is motivated to investigate the energy and manpower required in borehole method of making water readily available, starting from sumo pump to the packaging point, since it is beneficial to remote off-grid scattered settlement pattern in Nigeria.

Packaging of water is a means of providing the correct environmental condition for water during the length of time it is discharged from borehole, stored or distributed to the consumer. The packaged drinking water comes in many shapes and sizes such as bottle and sachet applications. There are three most common plastic materials used in packaging of water namely, polycarbonate, high density polyethylene and polyethylene terephthalate. For bottle or sachet usage, each material has its own quality issues.

The polycarbonate bottle has blemishes on its wall because of variations in production processes. It also requires a careful sanitizing procedure at the bottling plant in order to be fit for reuse; while for a high density polyethylene bottle, the spout may not always fit the cap, causing leakage in storage. The polyethylene terephthalate bottle requires its storage away from heat; an empty bottle could be deformed when stored at a temperature near 71°C, the filled bottle could consign a fruit taste to its water content if kept in an elevated temperature.

Besides the characteristic nature of the container, there are aesthetic conditions to be met [4], as well as sanitary inspection requirements [5] for example, washing solution application at 49 ^{0}C to 60 ^{0}C for five minutes, taste problems [6], and cap fitting issues encountered during packaging. Therefore, the bottle condition before the filling and after packaging of finished product is a critical success factor. To optimize the bottle appearance, polycarbonate PC redesign and regrind should be kept dry and processed within 20 minutes after drying and then keep all plastic regrind stocks free from contaminants [7].

There are previous studies on packaged water business and its importance to the human health. A recent work [3] described the concept of packaged water. It refers to water that is packaged generally for consumption in a range of vessels including cans, laminated boxes, glass, plastic sachets and pouches, and as ice prepared for consumption. The short-comings in quality of packaged water have been reported [8] and [9]. Igboekwe et el [10], identified quality parameters of concern in the use of borehole technology. The feasibility of this type of water supply system has been treated

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

[11], using willingness to pay method in estimating the benefits and costs. There is no doubt, from these reports that packaged water as a local initiative has led to improved accessibility to drinking water, but we are not out of the woods yet. Although the case for quality, aesthetics, inspection and feasibility have been clearly articulated elsewhere, the resource management and process optimization of packaged water operations are largely absent from the literature.

Better management of resources is a key in sustainable borehole water production if the MDG targets for water are to be achieved in 2015. For this purpose, this study investigated the processes that are involved in water packaging, starting with its extraction from the borehole to the sealing machine, determining of energy and manpower that are needed for packaging of water.

The specific objectives of the study include: to determine the gross energy requirement sequestered by the process, determine the man-power needed and finally optimize the process for most efficient packaged water management.

It explored possible ways of minimizing the cost of production and maximizing the profit through rational management of basic input resources involved, thus helping to provide solutions to the challenges that are facing them. All these course of actions will contribute to long term sustainability of energy and related resource input utilization. This evaluation is limited to energy and manpower resources required for packaged water factories within Nsukka and Enugu cities in Nigeria.

2.0 BACKGROUND INFORMATION

An investigation [12] showed that packaging of treated water started years back in Nigeria when people were using leaves, treated skin, vegetable fibers, coconut palm, earthen wares and later, nylon pouches as materials for packaging of water and it was manually operated[3]. In the old traditional Ibo setting, pre-heated banana and plantain leaves were the most common and widespread leaves used for wrapping food items. They were excellent materials for packaging products that are quickly consumed, as they are cheap and readily available. With the advent of improved water supply technologies and because of the importance of water packaging to the human population at large, packaging drew the attentions of the scholars, engineers and scientist which led to designing, producing and prescribing the most effective ways of treating and packaging water. In 1991 the facility for processing / packaging water was brought to Nigeria [7]. The facility has some challenges facing it in water packaging, among which was the need to determine the amount of energy needed and manpower requirements suitable for operating the factory as well as optimal utilization of available resources. The borehole technology is well suited to scattered rural settlement that is prevalent in Nigeria.

In addition to management of resources, the choice of Nsukka and Enugu cities is important, because they are hosting six campuses of tertiary institutions with estimated population of 100,000 students and increasing mobility of other persons. Therefore, water scarcity portends wide range of human health implications. Since energy is critical in discharging and packaging of the water, we therefore try to know the type and amount of energy that can be used in packaging of water and evaluate the energy, and manpower needed. The relevance of the topic to circumstance of our energy situation in Nigeria cannot be overemphasized.

2.1 Challenges packaged water factories face in Nigeria

The major challenges facing the water packaging factory in Nigeria includes: high cost of production, unreliable grid supply, high level of ineptitude, distribution problem and multiple taxation from the three-tiers of government. The issues of multiple taxation and distribution problems are beyond the scope of this study. The unreliable power supply is the cause of reliance on self-generating sets for production. As a result of the foregoing, cost of packaging operation is high.

High cost of production**:** The problem of high cost of production is there because of inability to quantitatively predict energy and pool of trained manpower required for a continuous operation. The inability to determine required number of trained hands on the job results in poor management of resources. Therefore the problem can be solved, if the optimal amount of energy, number of workforce and raw material are determined, accurately. As reported elsewhere, this type of system, also, cannot be sustainable if reliable energy and competent human capacity inputs are inadequate [13]. This affirmation therefore has necessitated the determination of the amount of energy needed to ensure its sustainable utilization.

Distribution of the produced water is a problem due to bad roads. For example a distance that will take a vehicle one hour, may last for three hours because of bad roads and this results in consumption of more fuels and damaging of vehicles used for distribution. On multiple taxation concern, the water factories should unionize, impliedly, the solidarity canvassed for here is meant to guarantee protection to major variables that drive cost of production- energy, labour and material if the entrepreneurship must be successful. As a possible solution to the high cost of production, this study decides to conduct a process evaluation and optimization of the production line. From this study prospective investor would have been better informed about the success factors for packaged water business.

2.2 Determination of energy and manpower requirements

Energy and Manpower can be determined using energy analysis which means determination of energy required in the process of making a good or service within the framework of an agreed set of conventions or applying the information so obtained. Once the system is defined; the energy requirements of the system can be determined.

3.0 MATERIALS AND METHODS

In this study, the production line was first broken down into basic operational units for logical evaluation. A typical in-situ packaged water factory consists of borehole, filtration, equipment housing/ piping, moulding and sealing / bottling machines units. A second step was to determine a weighting factor or amount of time for each operation. The next was determination of the energy and manpower requirements per unit.

Table 1: Process activity, equipment, time and energy involved in an in-situ water packaging factory

Stages	Power (kW)	Amt.of time (s)	Energy (J)	Machines used
1,2	3.0	3,600	10,800	Sumo pump
1,3	1.5	1800	2,700	Sumo pump
2,4	0	3600	0	Reservoir Tank
3,5	0	180	0	Storage tank
4,6	1.33	5,400	7,182	Electric pumping machine
5,7	1.33	18,000	7,182	Electric pumping machine
7,8	0	18,000	0	Supply tank
8,9	1.33	18,000	23,940	Electric pumping machine
9,10	0	18,000	0	Filtration plant
10,11	0.5	18000	9,000	Ultra-violent ray
11,12	1.5 (23)	18000	27,000 (414000)	sealing machine (bottling)
Total energy needed for one day =87,804J and 501,804J for sachet and bottle, respectively.				

Stages 1,2 and 1,3 involved water discharge from boreholes into storage tanks in 2,4 and 3,5. The meanings of other activities can be inferred from machines used in table 1.

3.1 Borehole

A borehole may be constructed for many different purposes, including the extraction of water or other fluids (such as petroleum) or gases (such as natural gas) as part of a geotechnical investigation, environmental site assessment, mineral exploration, temperature measurement or as a pilot hole for installing piers or underground utilities. In this context, boreholes are made for geothermal installations as well as pumping water from underground well. Typically, a borehole used as water well is completed by installing a vertical pipe and well screen to keep the borehole from caving. This also helps prevent surface contaminants from entering the borehole and protects any installed pump from drawing in sand and sediment.

Its power consumption, measured in terms of electrical rating of sumo pump machine is 4.5kW. The borehole technology is distinct for its low scale of production which suits scattered rural settlement.

3.2 Method of energy analysis

Energy and manpower requirements were determined using energy analysis technique. An energy analysis can be carried out from both a technical perspective and an economic perspective. An energy analysis from a technical prospective is called process analysis. An energy analysis from an economic perspective is called input-output energy analysis. For this study, the focus is on process analysis.

Energy analysis is important because it can be used to determine the energy invested in every step of the production process [15]. A survey conducted has shown that there is growing number of packaged water factories and their anticipated market expansion would require rational practices for profit and loss assessment of the production activity. In this study, linear programming is the optimization methodology proposed for decision making on profitability.

4. 0 RESULTS, ANALYSIS AND PROCESS OPTIMIZATION

In this study, project evaluation and review techniques (PERT) is used in process evaluation of energy and manpower needed in packaging operations. PERT requires three estimates of time for each activity. These times are combined to produce what is known as an expected time for a particular activity. With the estimated time and power consumed at the different stages, the process energy requirement is calculated as product of time and power consumption. Two major products, namely bagged (sachet) water and bottled water are produced from the process. Total energy consumed for each product line is 0.088MJ and 0.502MJ per day, respectively for sachet and bottled water production. The evaluated process activity outcome is presented in table 1.

When the machine makes a bag of water, it creates the bag from a continuous roll of polyethylene plastic material. For manpower involvement, an average of 0.075kW per normal human being is engaged [16]. By applying the human power index, the manpower requirement cost (MRC) index can be estimated as follows:

$$MRC_h = 0.075 N_h T_h C_h \quad [17] \qquad (1)$$

Where N = number of persons involved, T = time taken by persons for a given activity, C = cost/person

From the field survey, the manpower, energy and of quantity of water produced per day by nine out of 25 surveyed factories are shown in table 2. The nine factories use average 10 workforces and produce sachet and bottle water, simultaneously.

Table 2: Quantity of water produced, manpower (workforce) and energy used per day

Water produced in hectoliter per day, Y	Energy used by-the sector X_1 (KJ per day)	Manpower / workforce X_2 (man-day)
3.0	36.936	16
1.2	14.774	8
2.0	24.624	7
2.5	30.78	10
4.0	49.248	18
0.6	7.387	5
0.8	9.850	1
10	121.880	17
9	110.808	16

4.1 Decision analysis

A wide variety of criteria play a part in the viability of packaged water operation. The operation, just like every other business activity, is profit-oriented. It is important to assess all of the cost factors in order to determine how the most cost – effective plan could be obtained. Several methods were used and one of them was the cost analysis approach. We determined five important cost items that needed to be analyzed. These cost issues are:

- Power consumption
- Water production
- Material (packaging)
- Human resources
- Maintenance.

The first two cost issues analyzed cost of water production and energy use. The energy costs for water packing machine were disclosed, based on an electricity rate that was estimated by Power Holding Company of Nigeria (PHCN).

In addition to economic factors, quantitative information on fuel requirements, capacity of machines, number of labour and material that play roles in water packaging decision analysis were determined.

With the knowledge of these cost estimates, we can determine the profit profile of a typical water packaging factory.

4.2 Process optimization of production line

Since sachet and bottle products will compete for materials, energy and human resources, it is not clear which resource mix between the two products would be most profitable. Thus, Optimization is necessary to develop low cost strategies that will enable packaged water firms make decisions on how best to produce their goods at an affordable price. For the aforementioned reason, this study has determined a typical profit profile for both sachet and bottle water products as shown in table 3 for one of the sampled factories.

Table 3: profit profile for package water factory of two product capacity

S/n	Description of item	Product lines Bag (X_1)	Product lines Carton (X_2)	Available Investment Naira (₦)
1.	Selling price / unit	60	400	
2.	Direct raw material cost	2.7	24.20	42000
3.	Direct labour cost (in terms of energy)	2	1	4867
4.	Electricity usage and cost	15	230	5684.8
5.	Profit	40.30	144.80	

To optimize the profit, the constraints on input resources such as direct raw materials, labour and electricity are shown in table 3. These available investments in Naira (₦) values are limiting conditions for formulating linear programming algorithm for a production line.

Assumptions: the costs and incomes are assumed linear with quantity of products produced, thickness of material used is uniform and usage of each resource and its quantity are directly proportional to the level of each activity. The assumptions lead to formation of LP model with objective function, Z f (x_i) in equation (2).

Where f (x_i) = function of x_1 and x_2 variables, x_1 = units of sachet product; x_2 = units of bottled product; Z = objective function (maximization of profit). Mathematically, Maximize:

$$Z = 40.30X_1 + 144.8X_2 \qquad (2)$$

Subject to

$$2.7X_1 + 24.2X_2 \leq 42000 \qquad (3)$$

$$2X_1 + X_2 \leq 4867 \qquad (4)$$

$$1.5X_1 + 23X_2 \leq 568.48 \qquad (5)$$

Where

$$X_1 \geq 0, X_2 \geq 0 \qquad (6)$$

Using Gauss Jordan reduction technique, vectors (X_1 and X_2) that satisfy the set of constraint equations (3) to (5) can be determined. By solving these constraints analytically, X_1 = 1658 and X_2 = 1551. The profit per day based on these vector quantities is ₦291,428.29.

Multiple Regression Analysis

In order to translate the produced packaged (sachet and bottled) water in table 2 into requirement for inputs of manpower and energy a multiple regression technique is used. The quantity of water produced per day in table 2 was regressed with manpower and energy as independent variables using Statistical Package for Social Sciences, SPSS software version 16. The results of the multiple regressions are shown in tables 4, 5 and 6. Based on the regression analysis (coefficients in table 6), only energy significantly affects water production and the estimated regression parameter gives rise to equation 7. The R-square statistic has value of 1.0. This statistic is usually expressed in percentages and this result indicates that a total variability in quantity of water produced is completely accounted for by energy utilized.

Table 4: Summary of R-Square statistic

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	1.000[a]	1.000	1.000	27.67551

a. Predictors: (Constant), Manpower, Energy

Table 5: ANOVA[b] table for multiple regression

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	9.695E7	2	4.848E7	6.329E4	.000[a]
Residual	4595.602	6	765.934		
Total	9.696E7	8			

a. Predictors: (Constant), Manpower, Energy

b. Dependent Variable: Water

Table 6: Test of significance of regression coefficients

Model	Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
(Constant)	-2.508	21.527		-.117	.911
Energy	81.870	.295	1.001	277.786	.000
Manpower	-4.682	7.443	-.002	-.629	.552

a. Dependent Variable: Water

$$\hat{Y} = 81.87X_2 \qquad (7)$$

Where $\hat{Y} =$ quantity of water produced.

4.3 Discussion

4.3.1 Bagged water

In the bagged water system, the machine used is Argenpack 2500 and it produces 2500 sachets of 60 cl size per hour or 125 bags per hour. The Argenpack 2500 machine requires 1.5kW of power to operate and average production rate 42 kg of PET per day. Using this value, the machine produces average of 50 litres/kWh or 83.33 bags/kWh with plastic material consumption of ₦2.7/g and labour rate of ₦1.5/man-hour. From the utility tariff (Power holding company) we found that cost of 1kWh of electricity is ₦10 for industrial consumption.

4.3.2 Bottled water

For the bottling system, blown bottles can be made in-situ from performs or they can be purchased from plastic bottle vendors. In order to make bottle, the mode of operation a polyethylene terephthalate (PET) blow mold machine has been described in section 3.4.

The KBA 2500 consumes 23kW of power per hour. The cost of the whole system including air compressors and air purification and other accessories at local rate is ₦69, 565.3/kWh.

In order to make a 500ml bottle, material for perform is needed at the cost of ₦ 24.2 per perform. Filling, labeling, capping and packaging the bottles are each other issues entirely. To fill the bottles, an additionally piece of equipment called VP–50 from Venus packaging [18] is required. This machine fills approximately 2500 bottles per hour. The overall calculated cost of perform blowing into plastic bottle, water supply, filling, labeling and capping is ₦ 7. 73/ 500ml bottle.

The ANOVA test for the regression model indicates that the model is adequate to describe the relationship between water produced and energy and manpower utilized in an automated production line. In an automated process, machine displacement of labour is prevalent. This feature is significantly vindicated in the result of individual test of coefficients. The test for manpower's coefficient in table 6 revealed that manpower does not significantly affect water production. Therefore, there is direct relationship between water produced and energy utilized in the production such that little change in energy requirements have great influence on water production as shown in figure 1.

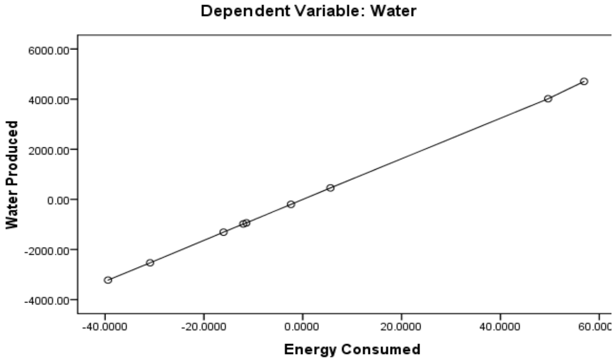


Figure 1: Effect of changes in energy consumed on water produced.

Also, it can be inferred from the foregoing discussion on the optimized production rates the facts that water packaging has a business implications and significance for Nigeria in meeting MDG targets for in 2015. As a business venture, it can add 3600 new jobs in 36 States of our country, thus, cutting down unemployment rate. In the MDG target, it increases access to portable water and also helps to avoid water borne-diseases.

5.0 CONCLUSION

This study presents a process evaluation as well as optimization of resources for a representative in-situ water packaging factory. It also, discuses the challenges faced by packaged water factories and the possibility of running them profitably. For profitability, the study determined a typical profit profile for a firm that produces both sachet and bottle water products. The study also shows the importance of using PERT when evaluating a production line.

Based on results of the study, the gross energy requirement sequestered by the process is 87.8J for sachet water and 0.52 MJ for bottle water packaging with average of 10 workforces. Also, the optimal production rates of 1658 and 1551 were determined for sachet and bottle water, respectively at a profit of ₦ 291,428.29 per day. The analysis of variance (ANOVA) test for the regression model indicates that the model is adequate to describe the relationship between water produced and energy and manpower utilized in an automated production line. Thus, we can advice someone to do the business as well as determine the amount of profit the business can generate per day. In conclusion, the study presents water packaging as a profitable business opportunity after evaluation of the required resources for its operation.

Acknowledgement

The authors are grateful to water packaging firms for their assistance in data collection and to Professor E. U. Odigboh, for proofreading the manuscript.

REFERENCE

References

[1] Lee, W., Liang, Z.Y., Sanchez-Torres, A., & Zhang, K. *Achieving Sustainable Clean Water Supply in South China.* Unpublished manuscript, Interactive Qualifying Project, Worcester Polytechnic Institute, 2005,Worcester, MA.

[2] Coca Cola Company's Sustainability Initiatives on Water. Available at http://www.scribd.com/doc/101202825 Accessed 06/10/2012.

[3] Ayokunle C. Dada. Packaged water: optimizing local processes for sustainable water delivery in developing nations. Globalization and Health, 2011, Vol. 7 (24) available at http://www.globalizationandhealth.com/content/7/1/24

[4] Gamache, C.W., Jorczak, K.D., & Schienda, A.M. (2001). *Nitrate Contamination in Eastern Puerto Rico's Ground and Surface Waters and Its Sources.* Unpublished manuscript, Interactive Qualifying Project, Worcester Polytechnic Institute, Worcester, MA

[5] Onemano, J. I. and J. A. Otun. Problems on water quality standards and monitoring in Nigeria. 29th WEDC

international conference: Towards the millennium development goals, 2003, pp 139 – 141

[6] Smith, M.A., HDPE, Phillips Chemical Company. *The Wiley Encyclopedia of Packaging Technology,* p. 519, 1986.

[7] Okolo, F. A. (2012), Personal communication. University of Nigeria water resources management laboratory, limited, Nigeria.

[8] Akpoborie, I. A., Ehwarimo, A. Quality of packaged drinking water produced in Warri meteopolis and potential implications for public health. J. Environmental Chem & Ecotoxicology, 2012, Vol 4 (11), 195 – 202.

[9] Ajayi, A. A., M. K. C. Sridhar, L. V. Adekunle, Oluwande, P. A. Qulaity of packaged water sold in Ibadan, Nigeria. African J. Biomedical research, 2008, Vol 11, 251 – 258.

[10] Igboekwe, M. U., A. O. Akankpo, R. A. Umenwa (2012), Groundwater monitoring at Micheal Okpara University of Agriculture Umudike for the determination of water quality. Energy and Environment Research, Vol. 2 (2), 21 – 27.

[11] Dutta-Roy, K., B. Thakur, T. S. Konar, S. N. Chakrabarty (2010). Rapid evaluation of water supply project feasibility in Kolkata, India.

[12] Onah, P. O., Onyia, I. E. Process evaluation of energy and manpower requirements for in-situ water packaging factory. Bachelor of engineering degree project submitted to Department of Mechanical Engineering, University of Nigeria, Nsukka, 2012.

[13] Ekechukwu, O. V., A. C. Madu, S. C. Nwanya, Agunwamba J. C. Optimization of energy and manpower requirements in Nigerian bakeries. Energy Conversion & Management, 2011, Vol 52, 564 – 568.

[14] KenPlas, (2006). Pet preform. Retrieved Mar. 24, 2012, from KenPlas Web site: http://www.kenplas.com/pp/petpreform/

[15] Khambalkar, V., Pohare, J., Katkhede, S., Bunde, D., Dahstonde, S. Energy and economic evaluation of farm operations in crop production. Journal of Agricultural Science, 2010, Vol. 2 (4), pp 191 – 200.

[16] Odigboh, E. U. (1997), Machines for crop production. In B. A. Stout (eds.), Hand book of agricultural engineering-plant production engineering, American Society of Agricultural Engineers.

[17] Jekayinfa, S. O., A. I. Bamgboye (2006), Development of equations for estimating energy requirements in palm-kernel oil processing operations, 2006, (accessed 10/10/2012).

[18] Venus Packing Machines PVT. LTD., (2006). Automatic mineral water filling machine. Retrieved Mar. 22, 2012, from Venus Packing Machines Web site: http://www.venuspackaging.com/primary.html

GCSM 11th Global Conference on Sustainable Manufacturing
2013 23rd - 25th September Berlin - Germany

3.5 Water management in sustainable manufacturing

P. Refalo, M. Zammit
Department of Industrial and Manufacturing Engineering, Faculty of Engineering, University of Malta

Abstract

Sustainable manufacturing and conservation of resources are more than just energy management. A broader perspective is necessary as stewardship of resources goes to further extents. Water management is expected to take a more pronounced role amongst the metrics for sustainability. This is backed by the reality that freshwater resources are facing extensive stresses which are leading to events of potential scarcity. Opportunities for water management exist in all areas of its demand, especially in the manufacturing sector being a key economic activity, dependent on natural resources. In a local scenario, the effects of water scarcity are on the rise. This paper discusses the relevance of water management for achieving sustainable manufacturing. An evaluation of the water footprint assessment tool is included, as applied in case studies in the manufacturing sector. The assessment method is evaluated against criteria relevant for assessing water sustainability in the local context.

Keywords:
Corporate Water Use; Sustainable Manufacturing; Water Footprint; Water Management; Water Scarcity.

1 INTRODUCTION

Water is central in every sector related to the society and the economy. Human activities are underpinned by the use of water, thus the importance of its availability. However, freshwater scarcity is a considerable issue which is attracting increasing attention from various bodies and sectors. Freshwater scarcity is factored by the inability of the supply to meet the ever-increasing demand. It is driven by a number of changes; such as the increasing population which brings about an increase in food, energy and water requirements. Climate change is an important factor which is expected to considerably affect countries which are already facing scarcity issues [1].

Given the dependence on water, enterprises are expected to be aware of the risks associated with water resources. Manufacturing is a key economic activity which is a major driver of economic growth. The manufacturing sector is traditionally associated with the intensive impacts on the environment. In this modern day and age, the sector should be thriving for sustainability. As part of the efforts towards achieving sustainable manufacturing, enterprises should not only minimise waste and become more energy efficient, but also exhibit water stewardship practices.

Water resources in Malta are facing considerable pressure, and scarcity is an unfortunate reality [2, 3]. Therefore, sustainable manufacturing in the local scenario should begin with enterprises becoming more sustainable in their own manufacturing facilities. Corporate attention to water management would therefore contribute to a lesser environmental impact. This paper addresses issues with water management in the local manufacturing scenario.

2 WATER AND MALTA

2.1 Water Scarcity

Locations with high population densities and which have low freshwater availability, are most susceptible to experience scarcity [1]. This description corresponds to the demographic description of Malta. Malta is an archipelago of islands in the Central Mediterranean Sea with a total area of 316 km^2. With a population of around 416,000, the islands are amongst the most densely populated countries in the world [4].

In coping with the demand, the country has been over abstracting from the natural groundwater reservoirs without allowing time for natural replenishment. The exploitation index indicates that 48% more than the groundwater sustainable yield is being extracted annually. This puts the island as one of the world's top ten water-scarcest countries [5]. The local scarcity issue also concerns a facet of quality, given that saltwater intrusion is degrading groundwater to a brackish quality. Nitrates also affect the quality of groundwater, which arise from the percolation of agricultural fertilisers. Climate change is a contributing factor which is expected to affect annual rainfall rates in a negative manner, thus reducing the availability of renewable freshwater [2, 3]. These factors are part of a broader picture of risks represented in Figure 1.

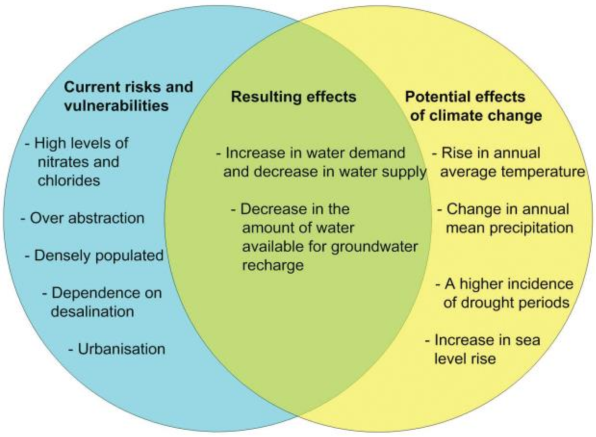


Figure 1: Overview of Risks and Vulnerabilities related to Groundwater [3].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2.2 Water Supply

Groundwater is the unique natural freshwater source in Malta, given that virtually no surface waters exist. The over abstraction of this natural source, makes the local water operator opt for desalinated seawater through reverse osmosis (RO) which is an energy intensive alternative consuming around 4% of the national electricity generated [5].

The local town water supply is a blend of approximately 44% groundwater and 56% desalinated seawater. Dependence on desalinated water is exhibiting an increasing trend. The main contributor to over abstraction of groundwater is that a considerable portion of national water consumption is unmetered, mainly through boreholes and non-revenue water. This is excluded from the 44% figure, a ratio which the local operator maintains in order to abstract only what is sustainably available.

Another unsustainable scenario which contributes to water losses, is the leakage in the urban water supply infrastructure. This pertinent issue is being addressed, with improvements being annually recorded [2, 6]. The present leakage factor accounts approximately to 14.8% of the total water supply [7].

Manufacturing facilities are connected to the town water distribution network. Town water typically requires a quality upgrade in order to meet process specifications, therefore demanding higher energy expenditure. Some enterprises opt for abstracted groundwater. This could either be pumped from a borehole within the vicinities of the factory or transported by bowser trucks from boreholes around the country.

3 WATER IN MANUFACTURING

3.1 Water Uses

This paper is concerned of promoting sustainable manufacturing in production facilities via water management. Therefore, a careful understanding of the uses of water in manufacturing operations is required. The direct water use in manufacturing systems could be classified in the following categories [8]:

- **Process Water:** Water used in the execution of manufacturing processes (such as in cleaning operations, transportation of material) or when it is incorporated as part of the product itself, serving as a raw material.
- **Cooling/Heating Water:** Water used to control the temperature of operations and equipment in the manufacturing facility. This portion of water use is required mainly by chilled water systems and/or cooling towers, which are used for machinery cooling and in boilers which are used for steam and heat generation.
- **Domestic Water:** Water used for the general sanitation and housekeeping of the manufacturing equipment and facilities. This includes service water which is the water used by employees for drinking and hygiene purposes. Water for irrigation may also be considered under this category.
- **RO Reject:** A by-product of the RO system which is more concentrated than the feed and can exhibit further uses (e.g. for domestic purposes).

Water operations in industrial facilities comprise a withdrawal from the supply, followed by a subsequent discharge into the sewer with a generally degraded quality. In Malta, all the discharge from industrial facilities should meet regulatory demands, and therefore enterprises treat their wastewater in-house before it is discharged into the sewer at a neutral quality level. This can be referred as consumption given that when water is treated in the municipal wastewater treatment plants, the treated sewage effluent is presently discharged into the sea, with negligible positive environmental effects. Plans for using this reclaimed water for second class uses are in the pipeline [6].

Indirect water use is also considered through the embedded water in the inputs and mechanisms of the manufacturing system, such as in raw materials, equipment and tooling [9]. Energy input incorporates an indirect water use due to water intensity in electricity generation. The water intensity in the generation of electricity is due to the generation of steam and cooling requirements. Therefore, this intensity is dependent on factors such as the plant technology (thermoelectric, hydropower etc.), energy carrier mix (fuel oils, gas etc.) and cooling technologies (once-through or recirculating) [9-11].

3.2 Corporate Water Stewardship

Enterprises are committing themselves to a more sustainable approach in their operations and corporate profiles. They are appreciating more the value addition which sustainable attitudes are contributing to their market performances [12, 13]. The idea that sustainability and profitability are two opposing factors in corporate performance, is nowadays considered an out-dated viewpoint [13]. As Figure 2 suggests, enterprises are still considering water sustainability as one of the lower priorities in their corporate agendas, where stewardship priorities lie with energy efficiency and minimisation of waste [12].

Figure 2: Key priorities for businesses [13].

The predicted increase in priority is mainly due to the potential risks associated with water scarcity [10, 12]. Water scarcity is highly localised therefore risks are also location dependant. These risks are termed as:

- physical risks;
- regulatory risks;
- reputational risks.

The above mentioned risks may all translate into financial limitations. Therefore, it results imperative that enterprises use their water resources in a more sustainable manner [14]. Corporate reporting is one initiative, where accounting of water use is important. Manufacturing enterprises are to implement water management practices, which may indicate improvement areas for sustainable water use, mitigation of environmental impact and disassociation from the water-related risks.

3.3 Water Management Methodologies

Resource management is based on prior resource measurement. A number of drivers lead enterprises to reduce their water consumption [12]. A breadth of tools exist which support the identification of improvement areas and promote water efficiency.

An interesting tool is the Water Management Hierarchy [15], which prioritises the solutions for decreasing water consumption. This hierarchy assists management in prioritising solutions.

Two systematic techniques are used to analyse water flows inside the manufacturing system and identify opportunities which promote efficient water use. This is achieved via process integration. Water Pinch Analysis and Water Cascade Analysis are composed of graphical and numerical techniques respectively, which implement reduction in water use in identified improvement areas. The techniques lead to implementation of reuse and recycling by analysing water flows and quality [16, 17].

Lifecycle Assessment (LCA) is a standardised tool under the environmental management family of standards, ISO 14040-14044. This tool is typically used to assess the environmental impacts of a product or service across its lifecycle and is composed of four phases: goal and scope definition, inventory analysis, impact assessment and interpretation. It has typically relied on accounting for energy and greenhouse gas emissions and rarely tackled freshwater consumption. However, this is now an active area of research [14, 18]. Arguments which outline the ineffectiveness of LCA in accounting for freshwater consumption and its impacts are also suggested in research [9].

As Jefferies et al. point out, another tool which is analogous to the LCA is the Water Footprint Assessment (WFA) [19]. The authors indicate both similarities and differences when addressing freshwater consumption using both tools. The WFA was developed by Prof. Arjen Hoekstra and it accounts for both direct and indirect (virtual) water uses, serving as an indicator of freshwater appropriation for human activities. The phases of the WFA are represented in Figure 3 [20].

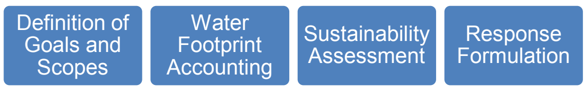


Figure 3: Water Footprint Assessment Phases.

WFA studies exist on the product level, where a supply chain approach is adopted to quantify water consumption along each production stage [19]. Ogaldez et al. point out that water consumption databases for manufacturing processes do not exist, compared to existent databases for crops [11]. The WFA Manual [20] then suggests that it is best to rely on data from the manufacturers when assessing manufacturing operations.

The WFA can be implemented on a number of levels, such as a manufacturing process, a product or a business [20].

4 BUSINESS WATER FOOTPRINT FOR A MANUFACTURING SYSTEM

Given the broad applicability of the WFA as an indicator for sustainability, this could be implemented on a basis of a manufacturing system. By definition, the water footprint of a business is the sum of the water footprint of the final products produced by the business. A business is an aggregation of different business units. A manufacturing facility fits the definition of a business unit [20]. The business water footprint enables an enterprise to calculate and report the freshwater consumption per year and/or per product [12]. The calculation is made according to equation (1).

$$WF_{Business} = WF_{Operational} + WF_{Supply\text{-}chain} \quad (1)$$

Schornagel et al. argue that the WFA is not suitable for industrial operations given that it does not balance flows inside the system [10]. This will be mediated by adopting elements from a water balance approach, and schematising water flow diagrams, in order to implement the WFA effectively as a tool for water management in a manufacturing facility [21].

4.1 Operational Water Footprint

The operational water footprint, $WF_{Operational}$ accounts for water consumption which occurs within the boundaries of the manufacturing facility. It is an aggregation of production and overhead operational water footprints. The former denotes the water footprint with a direct association to the production of end products and is the sum of process and cooling/heating water uses as described in section 3.1. The overhead is then equal to the domestic water use with all the activities as described above.

4.2 Supply Chain Water Footprint

The supply chain water footprint, $WF_{Supply\ chain}$, comprises the virtual water and is composed of two components. The production component denotes the embedded water inside the raw materials, equipment and tools, which are required for production. The overhead component includes embedded water in electricity, transportation and so on.

The characteristic components of the WFA are to be included when assessing water use in a manufacturing system. This decomposition will help assess the sustainability of the operational water footprint by distinguishing between renewable and non-renewable sources. The components are:

- **Blue Water** represents water sourced from the natural reservoirs. This comes from groundwater aquifers and constitutes around 44% of local town water supply. Borehole water and water purchased for drinking dispensers (e.g. 5 gallon bottles) contribute to this blue component.
- **Green Water** represents water sourced from a renewable source. This is considered when harvested rainwater is used in the production facilities.
- **Grey Water** represents polluted water-discharge such as wastewater from laundry, wash hand basins, water from machinery cleaning, etc.

The above factors are dependent on the availability and reliability of water-use data from the manufacturing site. When assessing for sustainability, the local context is to be a main criterion, given that the water footprint is geographically explicit [20]. The blue water footprint is highly unsustainable in the local scenario because of the pertinent over-abstraction problem. In mitigating this, alternative water sources should be considered. As such, the green water footprint will promote a more sustainable business water footprint when aggregating components. The focus of this work is on minimising consumption, and is minutely concerned of pollution, given that this is tackled by a legislative framework. Therefore, the attention will not focus on grey water.

5 CASE STUDIES

A number of manufacturing enterprises in Malta were approached to assess their water use and promote sustainable water management through WFA. The goals and scope of the study were defined. This meant that the business water footprint components to be included were those which had the water data readily available. In fact, supply-chain water footprint had to be omitted given that local manufacturers had no relevant data.

Water flow diagrams where schematised in order to better understand the flows in the manufacturing systems. Figure 4 represents the legend adopted for the schematic diagrams; the arrows on the left represent the water sources, whilst arrows to the right indicate what happens with the effluent from one process to another.

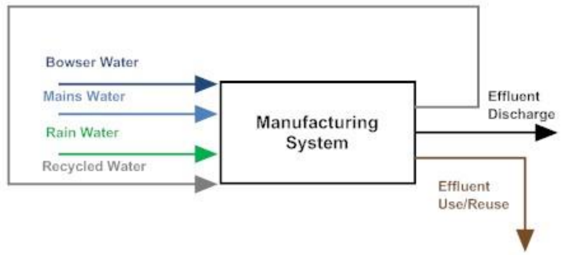


Figure 4: Water Flows in Manufacturing Systems.

5.1 Description

Two local small and medium-sized enterprises (SMEs) and one large company served as case studies. The case study companies are listed as following:

Case Study A: Seifert MTM Systems are manufacturers of industrial thermal management systems such as heat exchangers, air conditioning equipment and so on. The company employs 190 employees. Process water is used in surface treatments and cleaning. The rest is used for domestic purposes. They make use of an industrial chiller rather than cooling towers. Sources of water include borehole water and town water.

Case Study B: Pharmaceutical Company is a manufacturer of active pharmaceutical ingredients employing 35 people. Its name is kept undisclosed as requested. Process water is used in minimal quantities as a product ingredient but mainly for the cleaning-in-place of equipment between the production of different material batches. They exhibit a cooling/heating water footprint due to the use of a cooling tower and a boiler use. Apart from domestic water, a pronounced proportion of their operational water footprint is in rejected water from in-house reverse-osmosis plants and in backwash of sand filters. Water is sourced entirely from town water.

Case Study C: STMicroelectronics-Malta employs 1570 people and is one of the leading semiconductor manufacturers. It is also the largest manufacturing enterprise in Malta. Process water is the largest proportion of the operational water footprint and is used in wafer sawing and package cutting. Cooling towers provide cooling water and the domestic water footprint is quite pronounced given the large facilities, a 24-hour/7-day week operation, and the number of employees. This company recycles most of its process water, exhibiting excellent sustainability in terms of mitigation of environmental and social repercussions, with a positive financial gain. Sources of water include town water, rain water and recovered condensate from HVAC equipment.

5.2 Water Footprint Results

Data was made available by the companies through flow meter readings which are read periodically. Monitoring of consumption differs significantly between the case studies and thus the gaps in data availability and significance differed accordingly. Meter readings were aggregated in order to outline proportions between areas of water use, as this would potentially help identify areas of improvement. This is represented in Figure 5, with absolute values in m^3/annum and the respective percentage values. The figure also shows the water sources making the water footprint components, in order to aid sustainability assessment by distinguishing groundwater use from alternative water sources. The water footprint accounts help identify unsustainable footprints, such as the blue water component in all case studies and the RO reject water footprint in case study B.

This insight provides a basis for manufacturing systems to formulate responses, and implement water management practices which reduce the operational water footprint.

6 RESULTS ANALYSES

Results from case study A show that the domestic water use is more pronounced, meaning that water conservation efforts

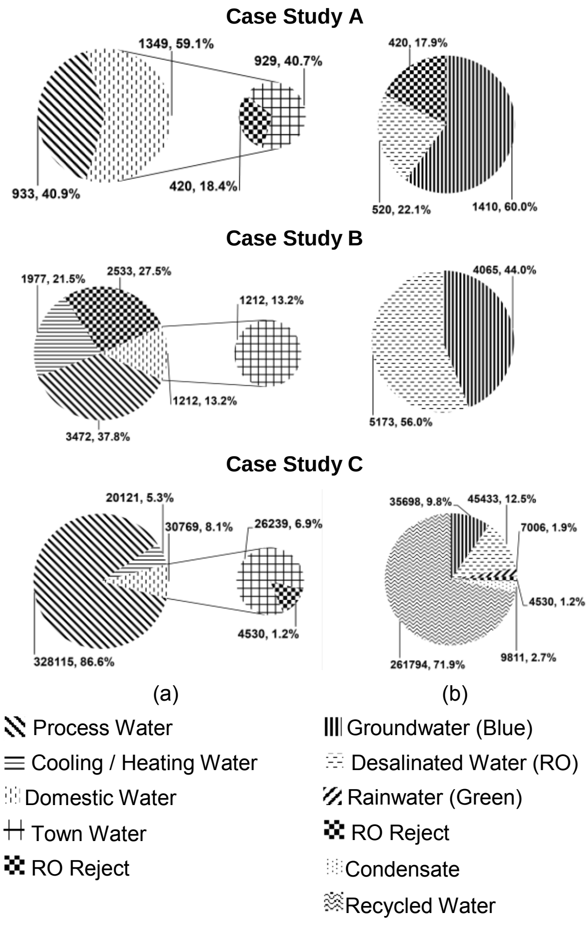


Figure 5: Results: a) Water Uses and b) Water Sources.

in this area would result in high savings. Process water is already minimised through water cascading. Given that this company makes use of chillers instead of cooling towers, a minimal amount of water is consumed for cooling purposes. More than a fourth of the operational water footprint of case study B is discharged RO brine. This could have other potential uses, such as in toilet flushing systems. This practice is wasteful and unsustainable. On the other hand, RO Reject is fully exploited by case studies A and C. The domestic water use in case study B is on the lower end given the low number of employees. Case study C requires most of its water for process use, however most of this is recycled, considerably reducing the operational water footprint. This case study taps into alternative sources of water.

Use of blue water and desalinated seawater is highly unsustainable given the direct pressure on water and energy resources respectively. In the case of a water scarce country, the use of natural water sources should be a last resort. This shows that case studies A and B have an unsustainable operational water footprint. Their footprint components show potential for the introduction of alternative sources such as rainwater harvesting and grey water recycling. This would offset the blue water footprint with a sustainable green one.

7 DISCUSSION

The case study results, indicated in Figure 5, provide a better basis on which improvements may be identified. The former provides meaningful information to manufacturing enterprises which want to reduce their operational water footprint in achieving sustainable manufacturing in their own facilities. The WFA provides the guidelines to assess for sustainability, such as for local water scarcity where attention is put in minimising the blue water footprint. Sustainability may be assessed on different levels, other than manufacturing facilities. The level of detail is also dependent on the impacts associated to the local environment. Following a sustainability assessment, together with the water footprint results, the improvement areas may be identified and solutions prioritised. Identification of water efficiency initiatives is required prior to their implementation. Following the results, a number of opportunities and barriers to water management could be identified.

7.1 Opportunities

With respect to the water management hierarchy [15], the identified opportunities were to start from replacing the use of freshwater with *alternative water sources.* This is proposed as a contribution to the mitigation of water scarcity, by reducing the blue water footprint. Rainwater harvesting is only performed by case study C, whereas this exhibits potential in the other companies, especially in case study A where the rainwater potential, found according to the local mean rainfall, would theoretically offset the current operational water footprint by more than 100%. Annual rainfall in Malta is at around 500-600 mm/a in 6-7 rainy months [2, 4] and therefore the potential for collection exists and remains to be locally exploited [6]. The quality of rainwater is suitable for second class quality water uses, such as cleaning and irrigation. Underground cisterns for rainwater harvesting also exhibit the potential for cooling by serving as a heat sink. Another alternative source is the recovery of condensate from HVAC equipment, which may also be exploited for reducing the blue water footprint. Case study B shows an exceptional water footprint of in-house RO-reject which is currently discharged to the sewer. Case studies A and C are examples of best practice in this case, where their reject streams are used for toilet flushing purposes.

Technology plays its role in reducing water consumption such as when considering cooling technologies. The existent methods show a distinction in terms of water consumption (e.g. once-through cooling against recirculating cooling). The water-energy link is evident in these considerations. Case studies B and C use cooling towers. Climatic considerations should also be apprehended. The local climate is typically hot and humid. Local manufacturing enterprises typically use cooling towers for normal operation and chillers as a backup in the hotter months. An estimate showed that, with the current utility prices, the energy cost associated with chillers would totally outweigh the water cost associated with cooling towers. This makes companies opt for the latter even though the former are negligibly water intensive and could be more suitable for the local climate.

Even though the *3R's (reduce, reuse and recycle)* have become more of a 'cliché', their implementation on a level of manufacturing facilities can yield a contribution to the minimisation of the operational water footprint. The domestic water footprint can be effectively reduced by implementing domestic retrofits such as faucet aerators to wash hand basins and water saving bags to flushing cisterns. These efforts may be enhanced by considering reuse and recycling of water streams. Case study C is an example of good practice in terms of recycling. However it is important to point out that daily volumes of water use may not always justify the implementation of recycling. Therefore, an enterprise-specific feasibility assessment is required.

Any successful water management plan is dependent on *management commitment.* This can be a driver to water management and more sustainable manufacturing simultaneously. The environmental management systems (e.g. ISO14000:1), should be used to meet not only environmental impacts in terms of discharge but also in terms of resource utilisation. The inclusion of water management as a company strategy would be a positive contribution [12]. This strategy may be extending from the operation of a manufacturing facility to corporate levels, where stakeholder involvement may promote demand for sustainable performance. Furthermore, this management drive can also lead to local industrial symbioses where companies in common industrial estates could collaborate in sharing their water resources.

7.2 Barriers

The *'business-as-usual' approach* resists change and keeps enterprises away from the adoption of sustainable measures. This attitude can also lead to an under-appreciation of risks as outlined in section 3. Proactive management, in conjunction to a paradigm shift would avoid such hurdle.

The *monitoring of water consumption data* exposed a number of issues from the case study results. Metering and sub-metering activity was found to be seldom rigorous. The practice of metering discharge flows is practically inexistent. These data gaps result in a difficulty to balance water flows and detect water losses such as in leaks.

Financial justification of water conservation projects can be considered the largest hurdle. This is mainly due to the current water tariff which does not include a resource and environmental cost. Therefore, local water pricing does not reflect the water scarcity scenario. This creates unattractive payback periods which do no not justify water conservation measures. This is especially true in cases of SMEs.

8 SUMMARY

This paper looked into the implementation of water management for promoting sustainable manufacturing in industrial facilities. The local situation of water resources was initially reviewed followed by a review of the relevance of water to manufacturing enterprises and some methodologies which support water management. The business water footprint was adopted as an indicator for sustainability and the operational water footprint was assessed in three case studies. The respective results provided a basis for which sustainability could be assessed. These results led to the identification of opportunities and barriers to water management in manufacturing.

The local manufacturing sector needs to become more water-sustainable. Opportunities for future work exist in determining the feasibility of certain initiatives, such as rainwater harvesting or wastewater recycling, which may support decision making in local enterprises. Feasibility assessments should include a technical and financial justification which would look into the cost-effectiveness of water conservation projects.

9 ACKNOWLEDGMENTS

The authors would like to acknowledge the support provided by the Malta Business Bureau (MBB)'s EU Life+ Investing in Water Project and also the enterprises listed as case studies for their collaboration.

10 REFERENCES

[1] UN-Water, "Coping with Water Scarcity: Challenge of the twenty-first century," 2007.

[2] FAO, "Malta Water Resources Review," Food and Agricultural Organization (UN), Rome, 2006.

[3] NAO, "Safeguarding Malta's Freshwater Resources," National Audit Office, Malta, 2011.

[4] NSO, "Malta in Figures," National Statistics Office, Malta, 2012.

[5] Cremona, M., Saliba, G., "Water Consumption Benchmarks - A step towards reduced consumption," in *Water: a 21st Century Challenge*, Malta, 2012.

[6] MRRA, "A Water Policy for the Maltese Islands," Ministry for Resources and Rural Affairs, Government of Malta, Malta, 2012.

[7] WSC, "Water Services Corporation - Annual Report: Key Performance Indicators," Water Services Corporation, Malta, 2011.

[8] Grobicki, A., "The future of water use in industry," in *Proceedings of the Symposium on Water Productivity in the Industry of the Future in UNIDO Technology Foresight Summit*, 2007.

[9] Wang, C., Seliger, G., "Water Footprint Method for Application on Industrial Products," in *The 10th Global Conference on Sustainable Manufacturing*, Turkey, 2012, pp. 711-716.

[10] Schornagel, J., Niele, F., Worrell, E., Böggemann, M., "Water accounting for (agro)industrial operations and its application to energy pathways," *Resources, Conservation and Recycling,* vol. 61, pp. 1-15, 2012.

[11] Ogaldez, J., Barker, A., Zhao, F., Sutherland, J. W., "Water Footprint Quantification of Machining Processes," in *19th CIRP International Conference on Life Cycle Engineering*, Berkeley, 2012, pp. 461-466.

[12] Lambooy, T., "Corporate social responsibility: sustainable water use," *Journal of Cleaner Production,* vol. 19, pp. 852-866, 2011.

[13] Fry, C., Somper, C., Parsons, W., Buldock, D., "Why are Business Leaders Prioritising Sustainability?," 2012.

[14] UN, "The CEO Water Mandate," USA, 2011.

[15] Wan Alwi, S., Manan, Z., Samingin, M., Misran, N., "A holistic framework for design of cost-effective minimum water utilization network," *Journal of Environmental Management,* vol. 88, pp. 219-252, 2008.

[16] Tan, Y. L., Manan, Z. A., Foo, D. C. Y., "Retrofit of Water Network with Regeneration Using Water Pinch Analysis," *Process Safety and Environmental Protection,* vol. 85, pp. 305-317, 2007.

[17] Klemeš, J. J., "Industrial water recycle/reuse," *Current Opinion in Chemical Engineering,* vol. 1, pp. 238-245, 2012.

[18] Lévová, T., Hauschild, M. Z., "Assessing the impacts of industrial water use in life cycle assessment," *CIRP Annals - Manufacturing Technology,* vol. 60, pp. 29-32, 2011.

[19] Jefferies, D., Muñoz, I., Hodges, J., King, V. J., Aldaya, M., Ercin, A. E.*, et al.*, "Water Footprint and Life Cycle Assessment as approaches to assess potential impacts of products on water consumption. Key learning points from pilot studies on tea and margarine," *Journal of Cleaner Production,* vol. 33, pp. 155-166, 2012.

[20] Aldaya, M. M., Chapagain, A. K., Hoekstra, A. Y., Mekonnen, M. M., *The water footprint assessment manual: Setting the global standard*: Routledge, 2012.

[21] Blair, T. A., "Industrial Water Use: Where'd It All Go? Balancing for Efficiency," *Proceedings of the Water Environment Federation,* vol. 2007, pp. 572-588, 2007.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

3.6 Sustainable uses and method for water treatment plant sludges

R. F. Reis [1], J. S. Cordeiro [2]
[1] Urban Engineering Department, Universidade Federal de São Carlos, Brazil
[2] Civil Engineering Department, Universidade Federal de São Carlos, Brazil

Abstract
Once Water Treatment Plant (WTP) for public supply is considered as an industry, it uses water as a source, chemicals and physics and biologic steps to treat the water and, obviously, generate waste, which is called as sludge. Most of these WTPs in Brazil use surface water as a source and a conventional complete cycle treatment type. The WTPs sludges are found mainly in clarifiers and backwash water filter. Unfortunately, most of Brazilian WTPs launches its sludge directly into water resources, without previous treatment, violating management practices and the Brazilian legislation. A solution for this sludge is to remove its water and after that, recycle the water removed and use the dried sludge in other activities, for example in ceramic production, in non-structural buildings and even to generate energy. This paper presents a natural and sustainable technology to dewater clarifiers WTPs' sludge and discusses possible uses for this processed waste.
Keywords:
Water Treatment Plant (WTP); Industry; Sludges; Dewatering; Systems; Drainage Bed (BD)

1 INTRODUCTION

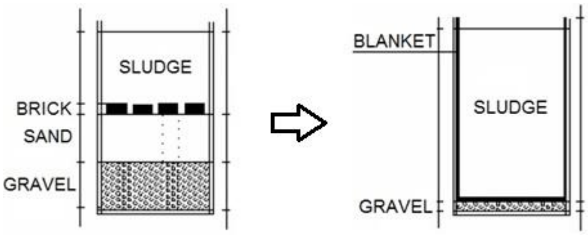
Water Treatment Plants (WTPs), which is a system to treat the water for public supply, for the reason of generating waste (sludges) with different characteristics, depending on the stream characteristics, the type of treatment (the type and amount of chemicals, etc.), is considered an industry. About this classification, the USA have published the "Clean Water Act" (PL 92-500), which establishes that WTP for public supply fall into industries classification and therefore should have its waste treated and disposed properly.

The act of thinking about treat WTPs sludges, due to its very fluid characteristic (1 to 5% of total solids), means to decrease its volume, which leads us to seek for possibilities to remove the portion of water from the content.

Dewatering systems for sludge in WTP, naturals or mechanicals, are essential for reduction of sludge volume and make its final disposal easier. Also, the efficiency of sludge dewatering depends on the required energy.

From researches carried out by Cordeiro [1], who developed a natural system of dewatering: the Drainage Bed – DB, and other studies conducted by Achon and Cordeiro [2], it was investigated the applicability and advantages of this system in comparison to other natural dewatering systems.

These studies with DB have been evolved with Barroso [3] and Achon et al. [4], who analyzed the influence of climate variables and realized that they are determinant during the phase of sludge drying. DB is a system that applies geotextile blanket as a filtering media, and it has more advantages when compared to other natural systems, due to its dewatering efficiency (drainage of free water), quality of the drained water and the possibility of drying the sludge by thermal processes (evaporation). This natural system was a result of an evolution of traditional drying beds, in which the filtering media is the sand. The Figure 1 shows this evolution described.



(a) (b)

Figure 1: Evolution from traditional drying beds (a) to drainage bed (b).

The aim of this paper is to show some sustainable dewatering methods and applications for WTPs sludges and the DB as an opportunity for WTP located in tropical countries due to results obtained with covered DB.

2 SUSTAINABLE DEWATERING METHODS

It is important to note that to this present paper the term sustainable dewatering methods consists of methods that do not require external/mechanical energy, but only natural one. Examples of these methods can be drying beds, bags and drainage beds (DB).

2.1 Drying beds

The traditional drying beds, as simply represented in Figure 1, is composed by three layers as a filter media: brick, sand and gravel. In some applications the brick layer is dispensed. To improve the filtering capacity, the sand layer is composed

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

by two or three layers with variable granulometry with total thickness of about 0.3 m.

There are occasions in which the background of the drying bed is a waterproofing layer, however, traditionally, the background is the soil itself. The operation of these beds should be performed observing the complete drying of the sludge from one to another discharge, as well as the height of the layer dumped that, after being properly spread, it is important to respect the maximum height of 0.3 m. Some advantages and disadvantages of using traditional drying beds are presented in Table 1.

Table 1: Drying beds system: advantages and disadvantages [5].

ADVANTAGES	DISADVANTAGES
- Low initial cost when the cost of land is low. - Low necessity of operation. - Low power consumption. - Low necessity of chemical conditioning uses. - High solids concentration.	- Necessity of extensive areas. - Necessity of work with stabilized sludge. - In the project design is essential to consider climatic variables, requiring some knowledge of climatology. - Require intensive labor to remove the dried sludge.

Although this system has several disadvantages, due to the low initial and operational costs, it is a dewatering WTP sludge alternative which is widely used. Examples of use of drying beds have been reported on the work developed in the United States by Murray and Dillon [6]. In this research were visited 469 dewatering WTP sludge systems, in which 47 of the total were drying beds, realizing a conclusion that 10% of the total systems visited use drying beds as sludge dewatering method.

2.2 Bags

In this technology the sludge is stored in large units which are shaped as a big bag. It is made of geotextile woven of high strength polypropylene, which performs two functions simultaneously: containment of solids mass and drainage of liquids present in the sludge. This drainage occurs through small pores, allowing the volume reduction of the contained waste and, obviously, decreasing the percentage of liquids present in the sludge. While the volume reduction is happening in a determined unit, this unit can be filled by repeated fillings until the available bag capacity is almost entirely occupied by the solid fraction from the waste.

Thus, after the consolidation of the material contained inside the bag, this is opened to properly dispose the sludge or reuse it in manufacturing processes of other products.

Figure 2 illustrates two cases of application of this system for dewatering WTP sludge in Brazil.

Figure 2: a) Curitibanos WTP – Santa Catarina State, and b) Santo Antônio do Jardim WTP – São Paulo State [7].

2.3 Drainage Beds (DB)

This system consists in a natural system of dewatering WTP sludge in which principles of operation and functioning are based on fundamentals of drainage and evaporation.

It is possible to affirm that just as the drying bed, the drainage bed has two operating steps that can occur simultaneously or not. One is the drainage of free water, and another the evaporation. The drain depends on factors related to the physical filtration (basically geotextile blanked used), but when chemicals are used obviously also depends on chemical factors, such as type, concentration and amount of polymer added to aid in the flocculation, what may result in a more effective dewatering. About the evaporation step, it depends on factors related to climate that may or may not be favorable to accelerate the water removal at this step.

The breakthrough considered in the drainage bed in comparison with the traditional drying bed is its highly initial drainage capacity – drainage of free water present in the WTP sludge – since the WTP sludge is extremely fluid. Cordeiro [8] [1] due to the fact of identify the necessity of initial drainage of free water, developed the drainage bed, which in its final design has only two filter layers, the geotextile blanket and gravel, with the blanket being the most important layer in the initial drainage of free water from the sludge. The geotextile blanket used in the DB has superficial density of 600 g/m² and is a nonwoven type.

In Brazil there are some WTPs that deployed the DB system and have succeeded in its operation. Some examples are the following WTPs: Cardoso (São Paulo State), Guanhães (Minas Gerais State) and Guaíra (São Paulo State). Figure 3 shows some pictures of Guaíra WTP.

Figure 3: DB Guaíra WTP: DB empty, DB filled with WTP sludge, WTP sludge dewatered, zoom in WTP sludge dewatered [7].

3 APPLICATIONS FOR WTP SLUDGE

As discussed in the previous item and in the introduction, the first step when it is thought about treating WTP sludge consists in dewater it, reducing its volume. However, performing only this step does not mean a sustainable treatment of this type of waste, but to make this treatment truly sustainable, it is necessary to give a proper allocation or application for this waste.

There are many potential uses for WTP sludge. Among these are available uses in the soil, cement manufacturing, bricks or ceramic manufacturing, commercial cultivation of grass, compost, commercial soil, citrus plantation, settling in water with low turbidity, coagulant recovery, H_2S control, discharge in collection network sewage, disposal in landfill, energy generation, etc. [9].

There are already real applications of all of these cited potential uses in Brazil and around the world. Nowadays, with the need to think of waste as an opportunity and not as a problem, the search for new potential uses of waste has intensified, including opportunities for the sludge.

In Brazil, the major application for dewatered WTP sludge has been to manufacture brick and ceramic, concrete matrix and in paving sidewalks for pedestrians.

Table 2 presents briefly some experiences of WTP sludge applications.

4 MATERIAL AND METHODS

Thinking about improvement of the DB dewatering method, it was developed some research conducted by Reis [7], in which it was made some essays in DB prototypes covered and uncovered, aiming better efficiency in the evaporation step, based on the premise that this dewatering technology would get better efficiency in tropical countries, like Brazil for example.

To conduct this research, DB prototypes comprised of a nonwoven geotextile blanket with superficial density of 600 g/m², samples of raw sludge from WTP and plastic covering were tested. Six comparative assays in DB prototypes with and without covering were performed at the same time for the evaluation of the drying phase by evaporation. Changing in sludge humidity was monitored by measuring the total solids.

Different heights of the plastic covering (varying from 0.2 to 0.6 m) were applied in the DB prototypes. For each assay, samples of sludge in prototypes were daily collected for dewatering monitoring in the phases of draining and drying (total solid content).

5 RESULTS AND DISCUSSION

Comparative results in DB acquired during seven days in the assay number 1 are showed in Figure 4.

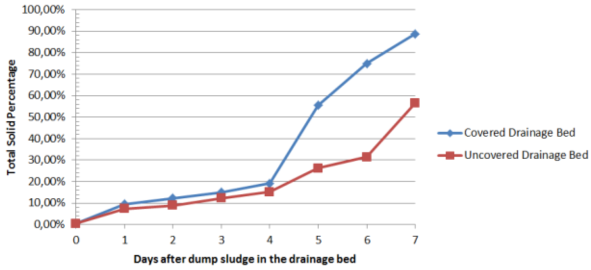


Figure 4: Total solid content in DB with and without covering (regard to the assay with height of plastic covering equal to 0.2 m in relation to the prototype border).

According to the graph (Figure 4), for the solid content in all DB assays, with and without covering, the most significant results were the assays number 1 and 6, which used the plastic covering with 0.2 m height, resulting in an increase of 30% in the total solid content. From Figure 4, it is clearly perceptible that the days in which occur simultaneously the drainage and evaporation steps are from the dump initial time until the fourth day. On the other hand, from the fifth day to the end occurs only the evaporation step, evidencing the best efficiency when the covering is used.

Figure 5 shows a comparison between the conditions of sludge on the seventh day from the assay number 1, which allows to visually realize the superiority of water removal from sludge and consequent reduction of volume in the covered drainage bed in relation to the uncovered one.

Figure 5: Conditions on the seventh day of sludge in the essay number 1 in the covered DB (left side) and in the uncovered DB (right side).

For the other assays with 0.3 m, 0.4 m, 0.5 m and 0.6 m height of the covering, the total solid content was lower, although it was always higher in covered DB.

6 CONCLUSIONS

The use of plastic covering in DB increases the ability of natural thermal drying (solar energy) and the same result may be expected from the use of this system in other tropical countries.

Furthermore, this research suggests possibilities for novel investigative studies with covered DB, with different coagulants uses, influence of initial total solid content in raw sludge, height of raw sludge applied in the DB, influence of climate variables, use of chemicals, applications to the sludge according to its amount of solids, etc.

Above all, it is important to note that, a promising theme to be investigated consists in alternatives/opportunities for the reuse of processed sludge. Thus, it is essential that technologies for sludge treatment does not only attempt to the dewatering of sludge, but also are linked to forms of reuse the waste dewatered, such as in power generation.

7 ACKNOWLEDGMENTS

We extend our sincere thanks to all who contributed to preparing this paper: SAAE São Carlos (SP), PPGEU UFSCar São Carlos (SP).

Table 2: Experiences of WTP sludge applications – case studies.

Author, application	WTP coagulant	Notes/considerations
Souza [10], application in concrete as aggregate	$Al_2(SO_4)_3$	In research aiming the waste reuse, he produced a composite of WTP sludge and sawdust to use as aggregate in concrete. The concrete containing the composite was prepared with the full replacement of conventional aggregates, characterized as non-structural lightweight concrete with thermal properties that suggest application in lightweight elements for sealing and thermal insulation.
Tartari [11], application in red ceramic manufacturing	Poly-aluminum chloride (PAC)	It was studied the incorporation of WTP sludge in red ceramic manufacturing and the results showed that the sludge presents characteristics of silty clays of low plasticity, being possible to replace similar clays up to 8%, according to the physicochemical properties specified in manufacturing standards for red ceramic cladding (brick).
Hoppen [12], application in concrete matrix	$Al_2(SO_4)_3$	The sludge was used in percentage substitution of the sand dry weight in cement matrices and the results showed that for substitution on 4 and 8% the concrete strength values were higher than 27MPa at 28 days, allowing multiple applications for this concrete, once they are non-structural application, since it cannot be certain predicted the behavior at long time. The viable applications are subfloors, sidewalks and residential floors, concrete covers for pit and pull boxes roofing, etc.
Costa [13], application in sidewalks	Aluminum polychloride (APC)	It was simulated the manufacturing of the concrete daily performed by the masons with the traces 1:2:3 (cement:sand:gravel) in mass and with visual monitoring of its workability. The viability analysis of the use of sludge as aggregate was based on axial compression tests and diametrical compression tests. These tests demonstrate that for traces using 5, 10 and 20% of sludge, it was obtained axial compression resistance higher than 15MPa, being considered as very good results, since for sidewalks are recommended values of 10MPa. About tensile tests there were no references, but even though it was possible to realize that the use of sludge as a compost with sand as fine aggregate interfere in the results, being recommended the use of percentages close to 10%.

8 REFERENCES

[1] Cordeiro, J.S., 2001, Processamento de Lodos de Estações de Tratamento de Água (ETAs), Rio de Janeiro: ABES, Projeto PROSAB.

[2] Achon, C.L., Cordeiro, J.S., 2004, Análise Crítica da Implantação de Sistemas Naturais de Remoção de Volume de lodo de ETA, San Juan - Porto Rico.

[3] Barroso, M.M., 2007, Influência das Micro e Macropropriedades dos Lodos de Estações de Tratamento de águas no Desaguamento por Leito de Drenagem, Tese (Doutorado), Universidade de São Paulo, São Carlos.

[4] Achon, C.L., Barroso, M.M, Cordeiro, J.S., 2008, Leito de Drenagem: Sistema Natural para Redução de Volume de Lodo de Estação de Tratamento de Água, Revista Engenharia Sanitária e ambiental - ABES - Rio de Janeiro, v. 13, n. 1, 54-62.

[5] Water Pollution Control Federation – WPFC, 1983, Sludge Dewatering – Manual of Practice, Washington, n. 20.

[6] Murray, K., Dillon, G., 1994, Waterworks Residuals Management: A Comparison of US and UK Practice, Washington: Management of Water and Wastewater Solids for 21st Century – A Global Perspective.

[7] Reis, R.F., 2011, Estudo de Influência de Cobertura Plástica na Remoção de Água de Lodos de Estações de Tratamento de Água em Leitos de Drenagem, Dissertação (Mestrado), Universidade Federal de São Carlos, São Carlos.

[8] Cordeiro, J.S., 1993, O Problema dos Lodos Gerados em Decantadores de Estações de Tratamento de

Águas, Tese (Doutorado), Universidade de São Paulo, São Carlos.

[9] Tsutiya, M.T., Hirata, A.Y., 2001, Aproveitamento e Disposição Final de Lodos de Estações de Tratamento de Água do Estado de São Paulo, João Pessoa.

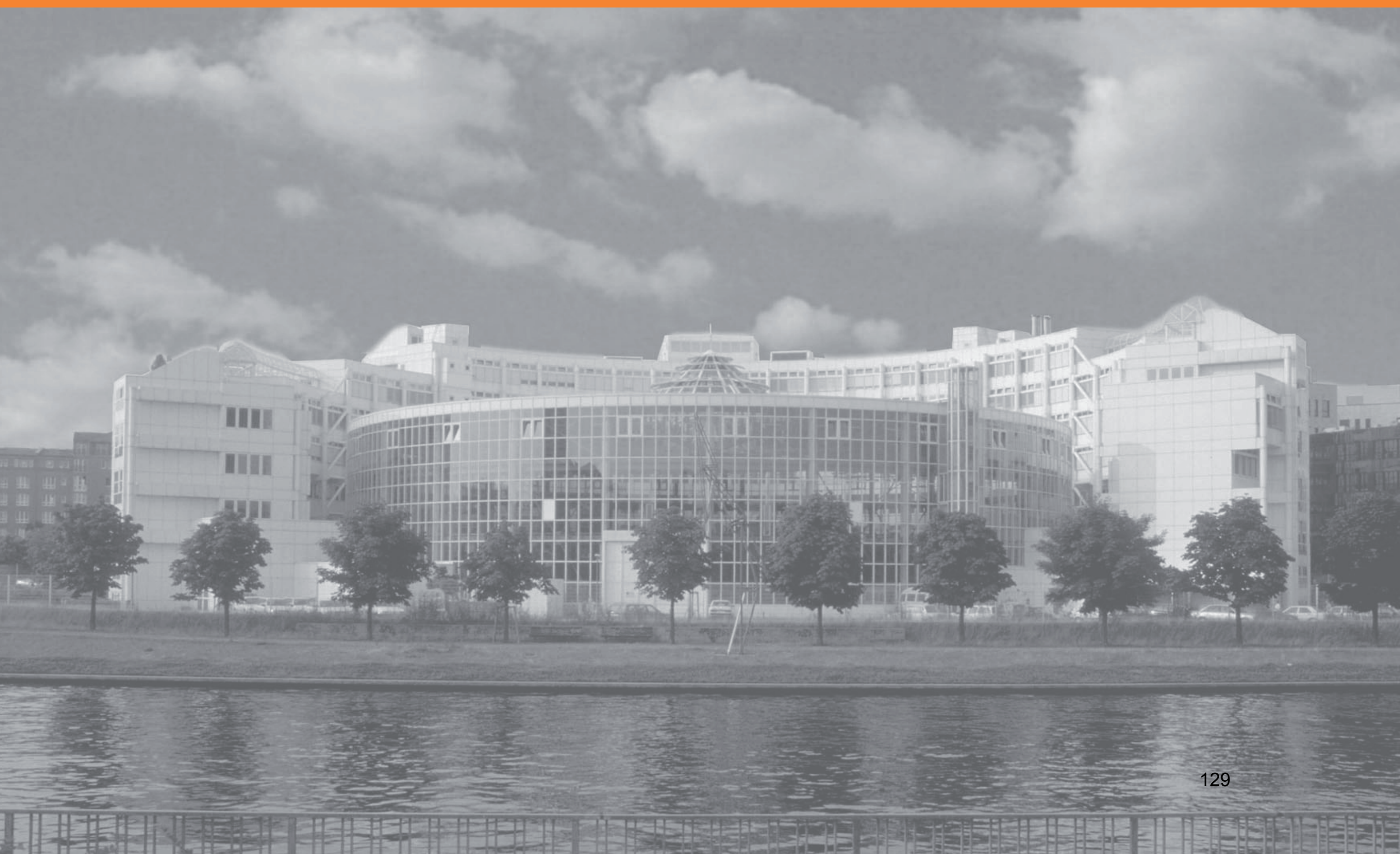
[10] Souza, F.R., 2010, Compósito de Lodo de Estação de Tratamento de Água e Serragem de Madeira para Uso como Agregado Graúdo em Concreto, Tese (Doutorado), Universidade de São Paulo, São Carlos.

[11] Tartari, R., 2008, Incorporação de Lodo Gerado na Estação de Tratamento de Água Tamanduá, como Aditivo em Massas para Cerâmica Vermelha, Dissertação (Mestrado), Universidade Estadual do Oeste do Paraná, Toledo.

[12] Hoppen, C., Portella, K.F., Joukoski, A., Trindade, E.M., Andreóli, C.V., Uso de Lodo de Estação de Tratamento de Água Centrifugado em Matriz de Concreto de Cimento Portland para Reduzir o Impacto Ambiental, Quim. Nova, v. 29, n. 1, 79-84.

[13] Costa, A.J.C., 2011, Análise de Viabilidade da Utilização de Lodo de ETA Coagulado com Cloreto de Polialumínio (PAC) Composto com Areia como Agregado miúdo em Concreto para Recomposição de Calçadas – Estudo de Caso na ETA do Município de Mirassol-SP, Universidade de São Paulo, São Carlos.

Session 4
Equipment



4.1 Improving energy efficiency of machine tools

T. Holkup [1], J. Vyroubal [1], J. Smolik [1]

[1] Research Center for Manufacturing Technology (RCMT), Czech Technical University in Prague, Czech Republic

Abstract

Manufacturing is responsible for about one half of global consumption of primary energy, a great deal of which is consumed by machine tools producing discrete parts. The topic of energy efficiency is driven forward by machine tool users who demand low operational costs, as well as social and legislative forces requiring environmentally friendlier manufacturing. This paper aims to provide examples and good practices for improving machine tool energy efficiency with a focus on metal cutting machine tools. During the design stage, there are various opportunities to minimize inherent energy losses by selecting and dimensioning drives and peripherals. On the other hand, users have a large impact on productivity by using the machine effectively and knowledgeably. The paper also presents techniques for measurement and analysis of the energy profile of machines which help to better target energy saving measures on already existing machines.

Keywords:

Design Modification, Electrical Power, Energy Efficiency, Machine Tool

1 INTRODUCTION

Manufacturing efficiency is an important factor for life cycle balance of production machines and their products. Former studies have shown, that the most important negative environmental impact of machine tools is the energy consumption during the use phase [1]. The energy costs also contribute to double-digit percentage of total life cycle costs, [2].

Energy efficiency of machine tools is a topical issue with motivation coming from several sides: machine manufacturers and users aiming at lowering processing costs, legislation requiring reduced environmental impact, as well as social aspects considered by customers and shareholders, [3] and [4]. Also CECIMO, the European Machine Tool Builder's Association, prepares a self-regulatory initiative for supporting the energy and resource efficiency of the machine tools produced in the EU [2]. The ISO 14955 standard 'Environmental evaluation of machine tools' [5] aims at improving energy efficiency by application of unified methods for energy consumption measurement, evaluation and reduction.

This paper summarizes experience gained through practical measurements and application of energy saving measures on metal cutting machine tools. Section 2 brings an overview of recommended methods for determining the energy profile of a machine. In Section 3 well tried general design principles for improving energy efficiency are mentioned. Section 4 introduce three case studies on three machine tools.

2 ENERGY PROFILE MEASUREMENT

The first task when measuring energy consumption of a machine tool is the decision on the system boundary. This topic is addressed in detail in ISO 14955-1 [5] even for rarer cases e.g. machines with waste heat exchangers. In most cases the machine is connected to the mains and to the central compressed air system which are enough to monitor.

The second task is choosing a relevant operating scenario typical for the machine. It should include productive time (typical workpieces, batches) as well as nonproductive time (stand-by, spindle idle run, warm up). If there is no 'typical' process specified, Research Center for Manufacturing Technology (RCMT) uses a workpiece from the TS B 0024-1:2010 standard [6] (Figure 1) suitable for milling machines with 3 and more axes. Scaling its size and cutting conditions is necessary to match machine tools of various sizes and spindle power.

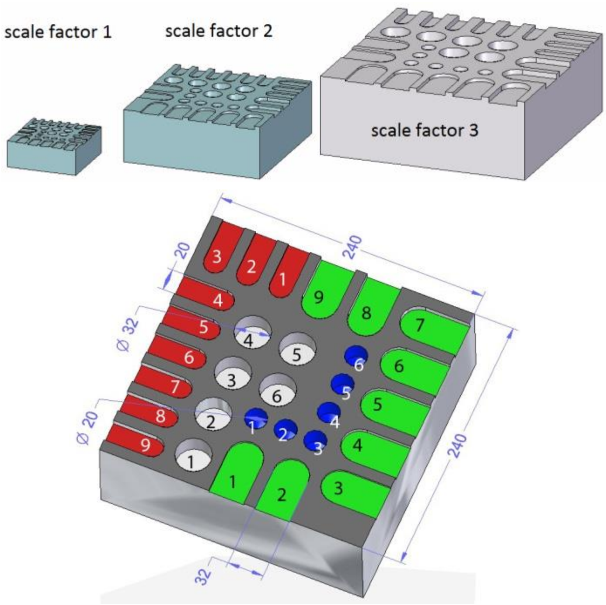


Figure 1: Test pieces including face milling, slotting and drilling with progressive cutting parameters, inspired by standard [6]; a) scale factors 1 (edge 120 mm), 2, 3; b) geometric details for scale factor 2.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2.1 Equipment for power measurement

The third task is choosing the equipment for basic energy consumption measurement. Figure 2 schematically shows standard electric circuits layout of a machine tool.

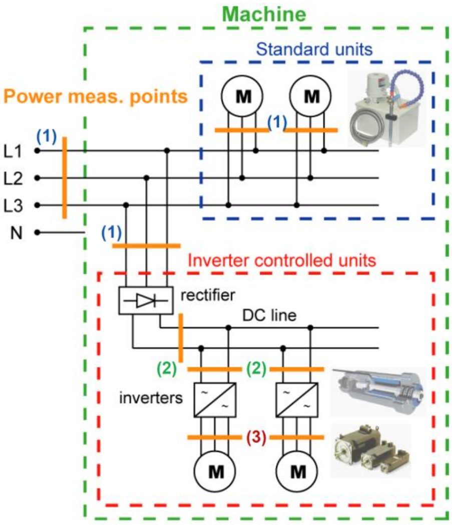


Figure 2: Schematic machine tool electric circuits with 3 types of electrical power measuring points: (1) 3-phase 50Hz AC, (2) DC line, (3) 3-phase AC with PWM voltage.

There are three types of energy flows which need to be monitored for obtaining the energy profile of a machine:

- 3-phase 50 Hz AC power measured at more locations by a multichannel equipment (type (1) in Figure 2);
- Power consumption of NC drives; RCMT uses current transducers based on the Hall - effect for monitoring currents from the DC line into inverters (type (2) in Figure 2); control system information is also an alternative.

Figure 3: Mounted Hall-effect current sensors for measurement on the DC link to drive inverters.

- Compressed air consumption measured by flow, temperature and pressure sensors; conversion rate for common 6 bar systems is approximately 18 W ~ 1l/min considering ideal compressor, 30 W ~ 1 l/min realistically.

In some cases it is advantageous to go for a more detailed analysis and also measure:

- thermal power (measured by thermometers and flow meters) for estimation of cooling power and efficiency of coolers / chillers or heat exchangers;

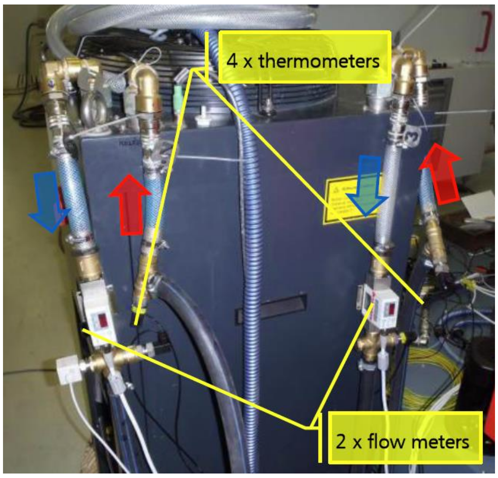


Figure 4: Cooling power and chiller's efficiency measurement setup on a two-circuit chiller.

- fluid power (measured by sensors of pressure and flow) for estimation of effectiveness of hydraulic circuits / components and efficiency of relevant pumps (e.g. cooling lubricant, Figure 7);

2.2 Basic energy consumption breakdown

Normally three basic energy flows into the machine tool and its components need to be monitored:

- spindle / axis NC drives;
- peripherals (electric);
- compressed air (converted to electrical power);

ISO 14955 suggests a functional approach, which is advantageous for comparing different ways for obtaining the same function within a machine tool. For example the function 'conditioning of the cutting process' can be performed by liquid coolants, compressed air, nitrogen cooling or minimum quantity lubr. (MQL). Their parameters including energy consumption will differ significantly.

There are various means of displaying the measurement results. These include pure time series, Sankey diagrams with component breakdown, pie graphs, or other graphs showing dependencies among parameters. Figure 5 shows the measured relation of machine total power consumption and the metal removal rate. Results show a pattern similar to the 'efficiency envelope' published in [7] and [8].

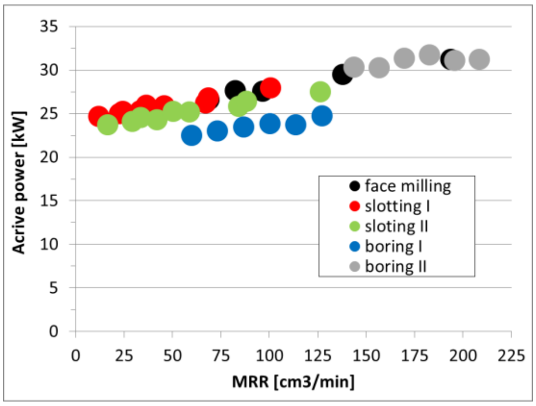


Figure 5: Power consumption in relation to machining intensity (machine TM1250, Case study 2).

2.3 Estimation based on a model

Using a computational model for estimation of energy consumption can be suitable during the design phase when no real machine is available for measurement.

RCMT has developed a model of machine tool energy consumption which consists of a list of energy consumers (main drives, peripherals), main machine parameters (moving masses, max. acceleration / velocity) and control information (mainly the PLC setup). The model can process a standard NC program in the ISO code (including M-function) and provide time-dependent series of parameters such as machine tool kinematics and power consumption of main drives and peripherals. The model uses the state-based approach from [2] and [9].

Simplified version of the model, the state / function breakdown of machine tool energy consumption, can help to estimate energy consumption during various operational scenarios. The functions are defined according to ISO 14955-1 [5]. Such model is based on the operational scenario and time shares of the machine states, example in Fig. 6. It cannot process the NC code, unlike the above mentioned full approach.

Both approaches need to be based either on measurement, analysis or on a qualified guess of power demands of respective components during different scenarios.

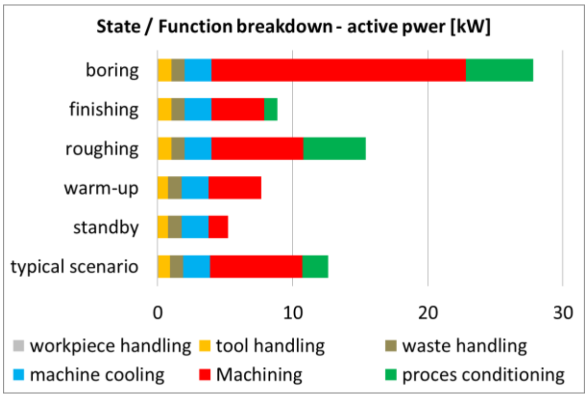


Figure 6: Example of ‘state / function’ profile of WHN13 CNC milling / boring machine (Case study 3).

3 ENERGY SAVING MEASURES

This chapter provides a list of well-tried principles for improving machine tool energy efficiency. These are based on RCMT’s own experiments which were inspired by ISO 14955-1 [3] Annex A, CECIMO LIP [10], or Fraunhofer IZM study [11] in the initial stage. The measures are divided into two main groups with respect to the phase of application: the design and the use phase. This general part of the paper is followed by selected practical examples.

3.1 Machine tool manufacturer - ecodesign

Saving measures are divided into groups according to their type:

Main drives

- The main drives (together with the machine tool frame) should mainly ensure effective manufacturing. Due to usually large share of constant ‘gray’ power in the total machine consumption: time = money; time = energy.
- The energy regenerative feedback from inverters and the rectifier (ER module) is usually not significant, unless the typical machine use scenario includes frequent tool change (spindle start / stop).
- The consumption of the linear axes is usually not significant.
- The energy efficiency of a milling spindle / turning spindle and its drive is of a greater importance and care needs to be taken to use an efficient (preferably synchronous) motor, transmission and bearings.

Peripherals

- It is crucial to know, what do we need from peripherals during various types of machining processes and ambient conditions (e.g. cooling lubricant quantity, cooling power of chillers). Oversizing of peripherals usually causes losses during the run with lower intensity.
- There are usually more design possibilities for providing a specific peripheral function; we need to be aware of the best available technology for a given purpose (e.g. the use of fluid-air fan cooling units with frequency control is sufficient for many machine tool applications, cheap and much more energy efficient compared to standard chillers) and seek for the best ratio of added value and energy demands.
- If the demands on peripherals depend on cutting process intensity, peripherals control targeting constant energy efficiency (e.g. frequency controlled pumps, example in Fig. 7, and compressors) is advantageous.

Fluid circuits

- These are: compressed air, cooling lubricant and hydraulic oil. The energy transformation from mechanic to fluid and back to mechanic always costs losses.
- Sometimes it is possible to avoid compressed air (e.g. replacing spindle air purge with advanced seals) or hydraulic systems (e.g. replacing hydraulic cylinders by electro-mechanical components) altogether. Such change usually saves a lot of energy normally lost in leakages and during energy transformation to the target functions.
- Being aware of the before mentioned conversion rate between compressed air flow and its electrical power equivalent.

Machine control

- Adaptive feedrate (automatic adjustments of the feedrate according to the tool, workpiece material, spindle speed, axial and radial depth of cut) helps to reduce machining time and ‘gray’ energy.
- Hibernation during nonproductive time with no user input (available in control systems from most manufacturers, needs PLC setup) after a specified time period. Automatic switching the compressed air supply off after the machine is stopped and the spindle cools down.
- Advanced compensation of thermal errors reducing warm-up time before precision machining.
- PLC setup enabling variable adjustment of machine peripherals according to variable minimal process needs.

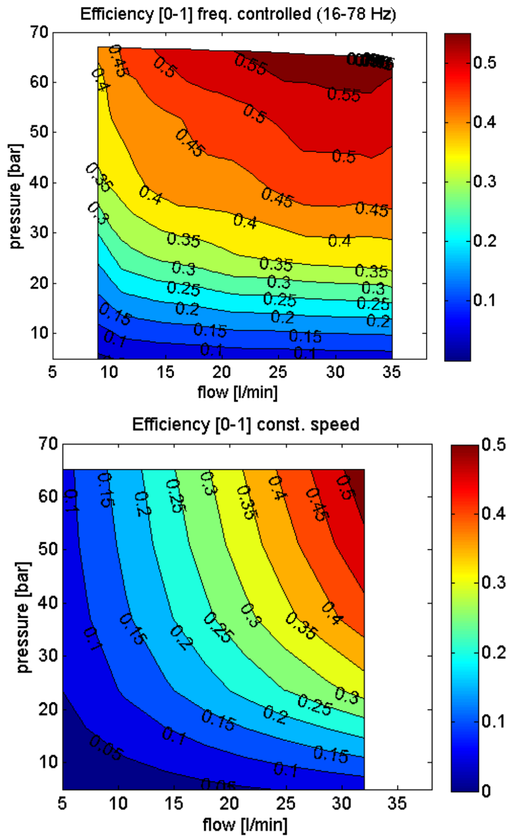


Figure 7: Example: efficiency of the high pressure cooling lubricant pump (ratio of hydraulic to electric power) a) frequency controlled, b) constant speed with relieve valve.

3.2 Machine tool user

- Machine tool selection according to particular needs; no oversizing.
- Selecting specialized machines for large series production when applicable (e.g. transfer machines, multi-spindle machines).
- Cutting conditions (tool, parameters, cooling lubricant) selection for productive machining. Devoting time and care to adjustment of the peripherals according to variable minimal process needs.
- NC tool path programming has usually a great potential for improvement during 5-axis machining.
- Reducing machine ON state to minimum. Process optimization OFF machine; using touch probes; automated tool / workpiece handling.

4 CASE STUDIES

The chapter presents the examples of three machines which have been subjected to:

- energy consumption measurement;
- analysis and suggestion of design improvements for improving the energy efficiency;
- application of design changes and measurement of their effect;

The three milling metal cutting machine tools are of different types. The testing scenario is based on manufacturing of the test workpieces (Figure 1) with scale factors 1-3.

The measurement results revealed that each of them had an obvious energy leakage. This could be fixed with low / medium effort and resulted in a double digit percentage of improvement. The case studies are presented in Table 1 - 3.

Table 1: Case study 1 - description and results

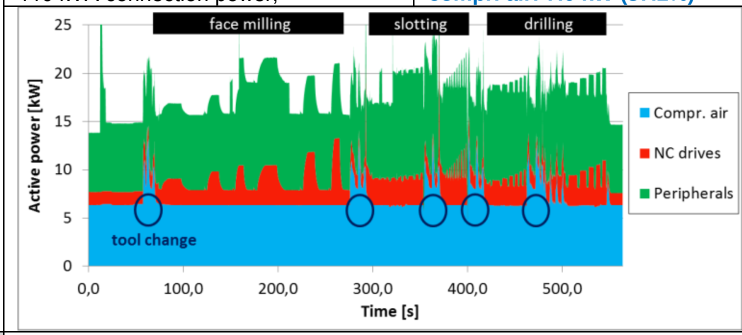
Case 1: Kovosvit MAS; MCU630V-5X; (workpiece scale factor 1)		**energy measurement results**
	5 axis milling center; 462 l workspace; 35 kW, 18000 rpm spindle; 110 kVA connection power;	**mean total: 18.8 kW** **NC drives: 2.7 kW (14.4%)** **peripherals: 9.1 kW (48.4%)** **compr. air: 7.0 kW (37.2%)**
	 	
analysis / main issue	NC drives' (5 axis + spindle) consumption is low, peripherals are also sized adequately. There is an obviously high energy demand related to compressed air. The pressure in the system is higher than necessarily needed for spindle air purge and linear axes measurement purge.	
solution	**Compressed air system redesign:** reduction valves mounted.	
power saved	The compressed air demand was lowered by 47%, which means: **18% of the overall machine active power consumption**	

Table 2: Case study 2 - description and results

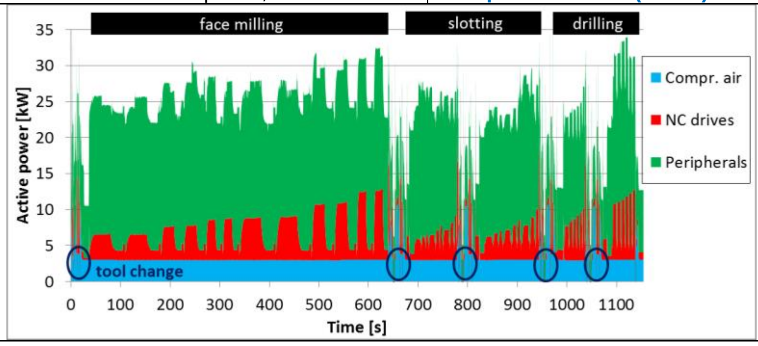
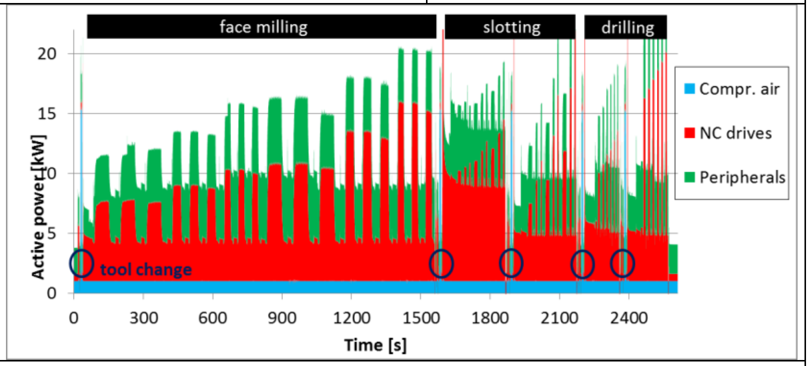
Case 2: Tajmac-ZPS; TM 1250; (workpiece scale factor 2)		**energy measurement results**
	4 axis milling / turning center; 2.62 m³ workspace; 48 kW, 6500 rpm mill. spindle; 100 kVA connection power;	**mean total: 23.8 kW** **NC drives: 4.0 kW (16.8%)** **peripherals: 16.5 kW (69.3%)** **compr. air: 3.3 kW (13.9%)**
	 	
analysis / main issue	NC drives' and compressed air consumption is adequate. There is a significant consumption of peripherals: mainly the high pressure central cooling lubricant pump (5 kW), the chillers for cooling the milling and turning spindles (4 kW) and the hydraulic pump with constant input of 3.2 kW	
solution	**Peripherals optimization:** the cooling lubricant pump was equipped with frequency inverter and user interface for active setup; the cooling circuits merged to a single system with reduced installed power and real consumption as well; the hydraulic circuit was optimized using a bigger accumulator and saddle valves; automatic hibernation of the machine during nonproductive time.	
power saved	Mean peripheral consumption was reduced by 28%, which means: **19.4% of the overall machine active power consumption**	

Table 3: Case study 3 - description and results

Case 3: TOS Varnsdorf; WHN13 CNC; (workpiece scale factor 3)		**energy measurement results**
	horizontal boring / milling machine; 11 m³ workspace; 46 kW, 3200 rpm spindle; 85 kVA connection power;	**mean total: 12.0 kW** **NC drives: 6.3 kW (52.5%)** **peripherals: 4.3 kW (35.8%)** **compr. air: 1.4 kW (11.7%)**
	 	
analysis / main issue	NC linear axes, peripherals and compressed air system consume relatively low power. However, significant consumption of the spindle can be observed during the spindle idle run (up to 8 kW during 3200 rpm).	
solution	**Spindle drive optimization:** the asynchronous motor of the spindle was replaced with a more efficient alternative; the transmission oil viscosity reduced; the lubrication of bearings was changed from grease to oil-air.	
power saved	The spindle losses have been decreased by 37%, which means: **15.4% of the overall machine active power consumption**	

Results show that relatively simple and straightforward saving measures can have a great impact in real. It of course depends on the initial level of machine energy optimization; nevertheless the nature of the problem is the same: finding the weakest point and fixing it.

5 SUMMARY

In this paper examples and good practices for improving machine tool energy efficiency with a focus on metal cutting machine tools have been presented.

There are no generic saving measures effective on all types of machines. Machines are different, and their energy efficiency weaknesses are even more so. This conclusion is absolutely in line with CECIMO SRI [10] argumentation to the European Commission when discussing the ecodesign legislation.

Very commonly, finding the weakest point in machine energy efficiency and modifying it with keeping the best available technologies in mind, makes a big difference in the overall improvement (similar to the “80% of problems - 20% of causes” rule).

When making ecodesign modification on a machine, it is always necessary to: a) measure with multichannel equipment / estimate the energy supplied to components; b) be aware of the best available technologies for specific machine tool functions.

Saving machining time per piece normally also saves energy. It means that machine designers and users can still keep productivity as the traditional main target. Also, even though machine designers do their best, energy-conscious user behavior is vital for energy efficient manufacturing in practice.

6 ACKNOWLEDGEMENTS

The paper “Improving energy efficiency of machine tools” has received funding from the Technology Agency of the Czech Republic (Project TE01020075). The authors also thank the companies Kovosvit MAS, a.s., TOS Varnsdorf a.s., TOS Kuřim-OS, a.s. and Tajmac-ZPS, a.s. for cooperation and contributing to the joint project.

7 REFERENCES

[1] Environmental Product Declarations – Product category rules, Milling machines case study, 2012, available at http://www.environdec.com/en/detail/?epd=8174

[2] A. Dietmair, A. Verl, Energy Consumption Assessment and Optimisation in the Design and Use Phase of Machine Tools, in: Proceedings of the 17th CIRP International Conference on Life Cycle Engineering, pp. 116-121, Hefei, China, 2010

[3] Joost R. Duflou, John W. Sutherland, David Dornfeld, Christoph Herrmann, Jack Jeswiet, Sami Kara, Michael Hauschild, Karel Kellens, Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals - Manufacturing Technology, Volume 61, Issue 2, 2012, Pages 587-609, ISSN 0007-8506

[4] S. Thiede, G. Posselt, C. Herrmann, SME appropriate concept for continuously improving the energy and resource efficiency in manufacturing companies, CIRP Journal of Manufacturing Science and Technology, Available online 6 April 2013, ISSN 1755-5817

[5] ISO/CD 14955-1, Environmental Evaluation of Machine Tools, International Organization for Standardization, Standard under development.

[6] TS B 0024-1:2010, Machine tools-Test methods for electric power consumption-Part 1: Machining centres, Japanese standard, 2010

[7] Zein A., Transition towards energy efficient machine tools, Springer-Verlag, 2012, 159 p.

[8] Gutowski, T., Murphy, C., Allen, D., Bauer, D., Bras, B., Piwonka, T., Sheng, P., Sutherland, J., Thurston, D., Wolff, E.: Environmentally Benign Manufacturing: Observations from Japan, Europe and the United States, Journal of Cleaner Production 13 (2005), pp 1-17.

[9] Verl A, Westkamper E, Abele E, Dietmair A, Schlechtendahl J, Friedrich J, Haag H, Schrems S (2011) Architecture for Multilevel Monitoring and Control of Energy Consumption. 18th CIRP LCE Conference, Braunschweig, p. 45–50

[10] CECIMO, 2009, Concept Description for CECIMO’s Self-regulatory Initiative (SRI) for the Sector Specific Implementation of the Directive 2005/32/EC. Online: http://www.ecodesign-info.eu/document-tations/Machi-ne_tools_VA_20Oct09.pdf.

[11] Schichke K., Energy-Using Product Group Analysis, Lot 5: Machine tools and related mchinery, Fraunhofer IZM, 2011, avaliable at http://www.ecomachinetools.eu

4.2 Energy consumption analysis of robot based SPIF

G. Ingarao[1], H. Vanhove[2], K. Kellens[2], A. K. Behera[2], F. Micari[1], J. R. Duflou[2]

[1] Department of Chemistry, Management, Computer Science, Mechanical Engineering, University of Palermo, Italy

[2] Department of Mechanical Engineering, KU Leuven, Belgium

Abstract

Production processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products, but are still poorly documented in terms of environmental impact. A thorough analysis of the causes affecting the environmental impact in metal forming processes is mandatory. The present study presents an energy consumption analysis, including a power study of Single Point Incremental Forming (SPIF) processes using a 6-axes robot platform. The present paper aims to investigate whether the fixed energy consumption is predominant or negligible in comparison to the actual forming operation. Power studies are performed in order to understand the contribution of each sub-unit towards the total energy demand. The influence of the most relevant process parameters, as well as the material being processed and the sheet positioning, with respect to the power demand are analysed.

Keywords:

SPIF, 6-axes Robot, Energy consumption, Sustainable manufacturing

1 INTRODUCTION

Production processes, as used for discrete part manufacturing, are responsible for a substantial part of the environmental impact of products. Nevertheless such processes, in particular non-conventional production processes, are still poorly documented in terms of environmental footprint. Thus, a thorough analysis on the causes affecting the environmental impact of these processes is a welcome contribution to increased knowledge in this domain.

Duflou et al. [1] provide a comprehensive overview of the state of the art in energy and resource efficiency improvement methods and techniques in the domain of discrete part manufacturing, with attention for the effectiveness of the available measures.

As far as metal processing technologies documented today are concerned, the reported studies predominantly focus on machining processes such as turning, milling and grinding, dealing with the influence of material removal and cutting fluids, in parallel with the electricity consumption [2,3,4]. Despite some exceptions [5,6,7], many other non-machining technologies, such as sheet metal forming processes, are still not well documented in terms of environmental impact. In this respect, the CO2PE!–Initiative [8] has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes and to provide guidelines to improve these. A methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) is provided by Kellens et al. [9]. The evaluation of the environmental performance of metal forming processes (bulk and sheet forming) is an urgent topic to be investigated since there is still a substantial lack of knowledge in terms of analysis and modeling of their environmental impact. Beside by substituting environmentally hazardous lubricants by new, less harmful ones [10]; the environmental impact reduction in cold sheet metal forming processes can be reached by minimizing the electrical energy usage and material waste .

The available literature on the environmental performance of sheet metal forming processes is typically limited to life cycle inventory analyses of air bending processes [11,12,13].In consequence a thorough analysis on the causes affecting the environmental impact in metal forming processes, especially the innovative but very energy intensive [14] (e.g. longer forming times, heat assisted processes, high pressure liquid, etc…) sheet metal forming technologies to form light-weight materials, is required. One of these technologies receiving increasing attention is certainly the category of incremental forming processes. In the simplest configuration (Single Point Incremental Forming, SPIF), the process setup consists of generic sheet clamping equipment and a hemispherical punch that incrementally forms the sheet toward a desired geometry by a proper trajectory on the sheet itself. Such incremental action allows avoiding the use of a rigid and dedicated clamping system. In consequence process costs and lead times are reduced. ISF (Incremental sheet Forming) processes also allow high formability compared to conventional stamping operations [15]. More recently, several researchers highlighted the ISF suitability for lightweight material processing: Duflou et al. [16] introduced a laser assisted local heating variant of the SPIF process, demonstrating that stress levels and springback effects could be reduced to obtain an improvement in terms of geometrical precision. In 2008, Ambrogio et al. [17] investigated warm incremental forming of magnesium alloy AZ31B, proving a formability enhancement by working magnesium in warm conditions. Other authors [18]investigated the hot incremental forming of titanium alloys by using electrical heating. As far as the environmental evaluation of such processes is

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

concerned, some first comparative environmental studies on incremental forming processes have been published by Ingarao et al. [19] and Dittrich et al. [20]. The latter paper presents an exergy analysis approach to compare - from an environmental point of view - incremental forming processes with conventional forming and hydro forming processes.

The authors of the present paper have recently developed an energy consumption analysis [21], including a power and time study, of Single Point Incremental Forming (SPIF) processes performed on a 3-axis milling machine. Principal conclusion of this study is that the first strategy to reduce the energy demand of SPIF processes is reducing the forming time by optimizing the tool path and working at the highest admissible feed rates. As the analyzed machine tools showed a very low machine tool efficiency, another strategy to improve the environmental performance of SPIF processes could be the redesign of the machine tool architecture in order to decrease the required power levels.

The present paper presents an energy consumption analysis, including a power study of Single Point Incremental Forming (SPIF) processing based on a 6-axes robot. The overall objective of the study is to identify the most energy efficient hardware solution for SPIF processing. Power studies have been performed in order to understand the contribution of each sub-unit towards the total energy demand. The influence of the most relevant process parameters (e.g. feed rate, step down), has been analyzed. Moreover also the effects of the material being processed and of the sheet positioning on the power/energy demand are analyzed.

2 CASE STUDY SPECIFICATION

The experimental study was aimed at manufacturing a truncated cone(shape commonly used to analyze SPIF processing) with a wall inclination angle of 45°, a maximum diameter of 120mm and a final depth of 40mm. A 6-axis Kuka KR210 robot was used during the tests. In order to form the AA-5754 aluminum alloy sheets with a thickness of 1.5mm, a hemispherically shaped punch with a diameter of 10mm was utilized and mineral oil was used as lubricant. The applied feed rates and step down values for the different tests are listed in Table 1. A free spindle rotation (the spindle was left idle and free to rotate, so that tangential friction would make the tool rotate) was used.

Table 1: Applied parameter settings for the developed tests and resulting forming time

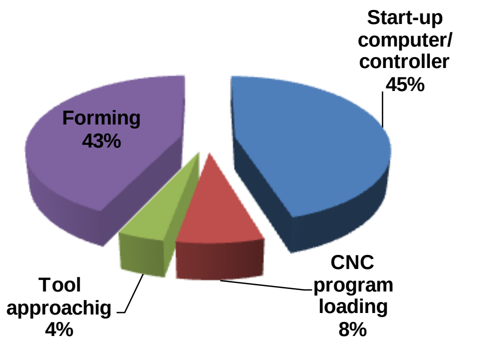
Test ID	Feed rate [mm/min]	Step down [mm]	Forming time [s]
1	2000	1.0	287
2	1000	0.5	1141
3	2000	0.5	575
4	1000	1.0	579

3 LIFE CYCLE INVENTORY (LCI) DATA COLLECTION

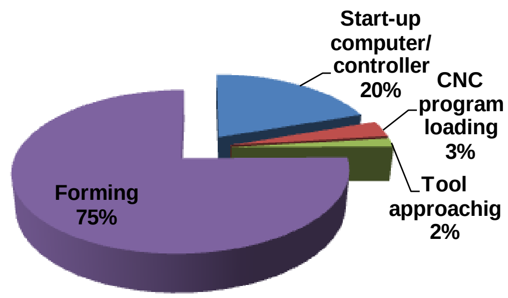
This section reports the results of the performed LCI data collection effort.

3.1 Working cycle time study

A time study was performed in order to identify the different production modes of the considered machine tool and their respective shares in the covered time span. For this purpose the machine tool was monitored during multiple working cycles. The identified production modes cover the machine tool start-up, use phase as well as shut-down operation. Figure 1 shows the averaged time share of the different production modes for two different parameter settings: the fastest process variant, Test 1 (Figure 1a), and the slowest one, labelled Test 2 (Figure 1b).



(a)



(b)

Figure 1: Time share for different production mode for Test 1 (a) and Test 2 (b)

As can be concluded from Figure 1, even for the fastest process parameter settings (Test 1), the time share of the productive mode (forming mode) is dominant. Comparable to machining processes, the productive time is substantial. Applying the process parameter settings of Test 2 (Table 1), results in a forming time share rise up to approximately 75%. It is necessary to underline that the shape taken into account in the present study is a very simple one; the forming time (and related share) for industrial products can be expected to be substantially higher, while the duration of the other modes is product shape independent.

3.2 Power/Energy study

The energy consumption is determined by the supplied average power multiplied by the duration of an operation. In order to estimate the energy usage in each phase, the consumed electrical power was measured for all the identified production modes. For each production mode, the total power demand as well as the power demand of all relevant sub-units were monitored by using electrical power meters with a sampling rate of 12.8 kHz (results logged and shown are for averaged values over 1 second intervals). The measurements were repeated for all tests listed in Table 1. Once the power and the time values were collected, the corresponding energy consumption was determined. Table 2 reports the times and the energy calculated for Test 1. To better illustrate the power demand over a full working cycle, Figure 2 reports the power profile registered for Test 1. From the power profile shown in Figure 2, three main power levels can be distinguished: the start up/computer controller power level of approximately 220W; the tool approaching phase, characterized by a peak corresponding to a fast positioning of the robot and a subsequent power level equal to 630 W; and the productive (forming) power level. The productive phase is characterized by a growing trend: such increasing trend, as will be better explained in Section 4.2, is due to the hardening phenomena of the material being formed.

Table 2: Energy consumption and related times for each production modes for Test 1

Production mode	Time [s]	Energy [kJ]
Start-up computer/controller	300	66
CNC program loading	50	11
Tool approaching	27	18
Forming	285	208
Total	662	303

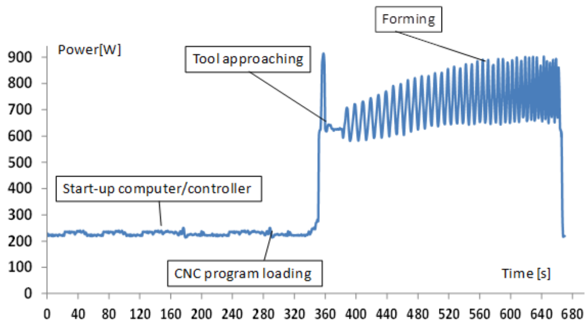
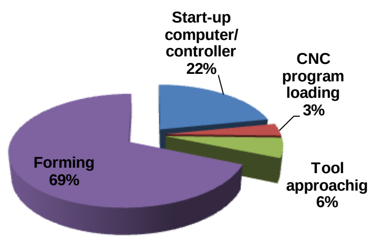
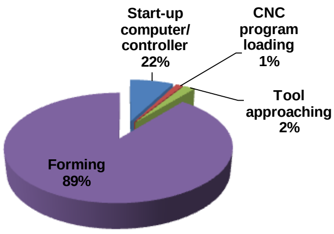


Figure 2: Power profile for Test 1

A cross analysis of Figures 2 and Table 2 allows to conclude that the power consumption in the productive forming mode is dominant, i.e. the energy demand during the forming step is much higher in comparison to the other production modes. Figure 3 shows the energy share of the different modes for both Test 1 (a) and Test 2 (b). For the faster operation the forming mode accounts for 69% of the total electrical energy consumption while for the parameters settings of Test 2 (the slower one) the energy share of the forming mode rises up to 89%.



(a)

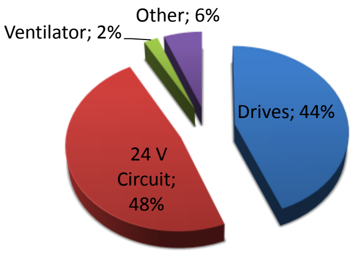


(b)

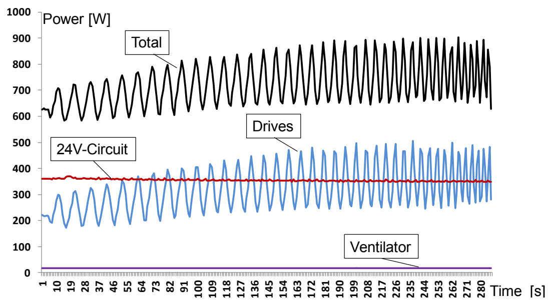
Figure 3: Energy share for Test 1 (a) and Test 2 (b)

3.3 Sub-unit breakdown analysis

The power demand of relevant sub-units was also measured for all production modes. This helps to understand the cause of the energy consumption and facilitates the identification of strategies to reduce the total energy demand and related environmental impact (e.g. by selectively switching off non-required sub-units). Since the dominance of the production mode was demonstrated in the previous section, the sub-unit breakdown analysis during the forming step was analyzed in detail. The used robot has three main sub-units: the drives, the 24V-circuit (for all low power electronics for the control cards including drives control) and the circuit for the ventilator. For each sub-unit, the power profile was measured and the energy consumption was determined. Figure 4 (a) shows the breakdown analysis. As can be observed, the drives and the 24V circuit play a relevant role, accounting for almost the total of the energy consumption. Actually the drives and the 24V circuit account for 44% and 48% respectively. In Figure 4(b) instead all the sub-unit power profiles registered for Test 1 are simultaneously plotted. It can be observed that the increasing trend of the total load curve is totally due to the power demand in the drives that, actually, move the tool to form the sheet, and as a consequence belong to the only sub-unit sensitive to the material hardening effect.



(a)



(b)

Figure 4 Sub-unit breakdown analysis (a) and sub-unit power profiles for Test 1(b)

4 ENERGY AND POWER INFLUENCING FACTORS

4.1 Influence of process parameters

In order to analyze the influence of the step down and of the feed rate on the power demand, the average power level and the energy demand during the forming phase have been measured for all the conducted experiments. The developed tests represent a complete two levels two factors array. In consequence it is possible to analyze the effect of each single parameter. The results are reported in the Table 3; as it can be seen by moving from the low level value to the high level value, the influence of a single parameter on the power level is limited to about 4 %, and even by changing both parameters simultaneously, the influence on the average power value is only about 6%. On the contrary, it is necessary to consider that by changing one of these parameters the forming time can double (compare forming times for Test 1 and 3 or Test 2 and 4 in Table 1). The measured small power variation due to these parameter settings (limited to 4%) can be neglected in every electrical energy oriented analysis. The conclusion is that the step down and the feed rate significantly influence the energy requirement only because these parameters strongly affect the forming time. Table 3 reports also the total energy measured for each test. Considering the fastest working cycle (Test 1) as reference base for the energy demand, the additional energy consumption for the other configurations is reported.

Table 3: Energy and power results for the developed tests

Test ID	Energy [kJ]	Average Power [W]	Additional Energy Consumption
1	208	724.9	/
2	781.6	685	276%
3	401.3	698	93%
4	407.7	704	96%

Figure 5 reports the energy demand for all the parameter settings (Tests 1-2-3-4) listed in Table 1. As expected, a decrease of the step down and/or feed rate results in a longer forming time. In consequence, the energy demand rises as well. The linear trend of the forming energy as a function of the forming time further proves the forming time dominance.

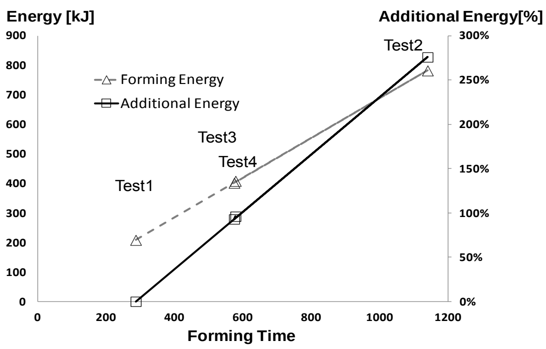


Figure 5: Energy demand and Additional energy for the developed tests

4.2 Material contribution to the power/energy demand.

In order to analyze and quantify the effect of the material contribution itself on the power demand, the power profile obtained while a material is being formed has been compared with the power profile obtained in air forming conditions (the air forming process was developed by keeping the same process parameters but without the presence of the material itself). In order to cover a quite wide material properties range, three different materials have been selected: a very soft aluminum alloy (AA-1050) characterized by very limited hardening, a high strength aluminum alloy, namely AlMg03 (AA-5754), and finally also DC01 steel was tested. Due to technical constraints in all the tests a feed rate equal to 2000 mm/min and a step down equal to 0.5 mm were used. For all three materials the sheet thickness was equal to 1.5 mm.

In Figure 6, the power profile related to the air forming conditions and the ones related to the AA-5754 aluminum alloy and to the DC01 steel are reported. For the soft AA-1050 material, only a slight increase in power demand was observed. In particular since the material is characterized by limited hardening, the related power curve is not characterized by an increasing trend, but, on the contrary, only a slight offset of the air forming power curve was observed. When considering the other materials, it can be noticed in Figure 6 that the power profile is characterized by an increasing trend. The stronger the material, the more noticeable is the growing trend. This phenomenon can be explained by the material hardening effect during the forming phase.

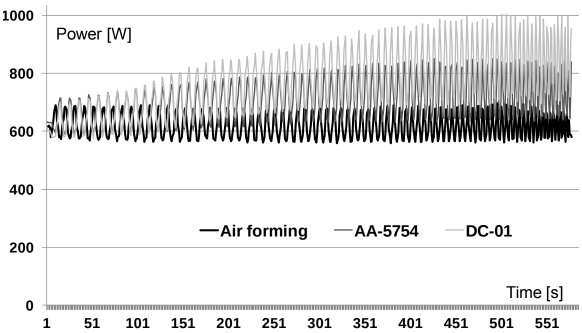


Figure 6: Power profiles comparison for varying material strength

The electrical energy, the average power level as well as the contribution of the material share on total power demand are reported in the Table 4..

Since the air forming energy is constant and equal for each test, at the increasing of the material strength the energy demand increases considerably and as a consequence, the material contribution share on the energy demand considerably increases as well. More in details the material being formed accounts for the 3% in the case of the softer material and account for up to the 22% for the DC-01 steel.

Table 4: Results of varying the material

Material	Energy [KJ]	Average Power [W]	Material contribution share
Air forming	358.6	619.4	/
AA-1050	368.8	636.9	3%
AA-5754	408.0	704.6	12%
DCO1	459.4	793.4	22%

4.3 Effect of the sheet positioning

The sheet positioning is another parameter to analyze from the energy demand point of view. Actually at the varying of the sheet position, the motors, driving the different axes, are used under different load conditions and the energy demand could be affected by such phenomenon. In particular, the sheet clamping equipment has been shifted over a distance of 600 mm, in the mounting rig shown in Figure 7. Such change has increased the lever of the mechanical moment the drives of the robot have to apply to form the material.

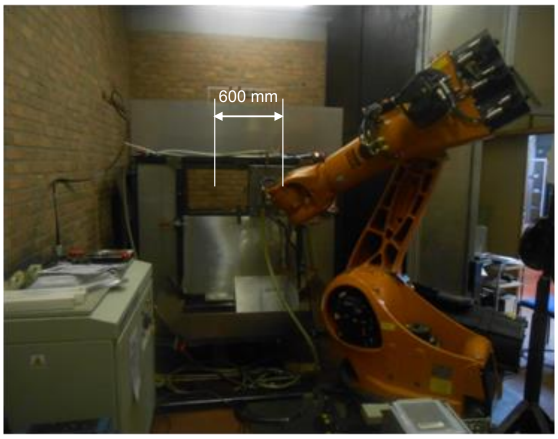


Figure 7: Setup for the analysis of the sheet position influence

It was expected that such mechanical moment increase could result in an increase of power level as well. In particular again the three mentioned tests with the three different materials were developed and also a power measurement for the air forming condition was performed. As could be expected, no relevant difference in power demand was observed between the air forming condition and the case of the soft AA-1050 forming process. On the contrary, as the strength of the formed material increases, the differences in terms of power level are relevant between the two different positions. In particular developing the experiment in the shifted position leads to a noticeable increase of the power demand. In Figure 8, the comparison between the power profiles obtained in the two different positions for the DC01 case are reported. As can be noticed from these results, even a relatively small sheet displacement results in a substantial power increase. In particular, the stronger the material the higher is the power increment.

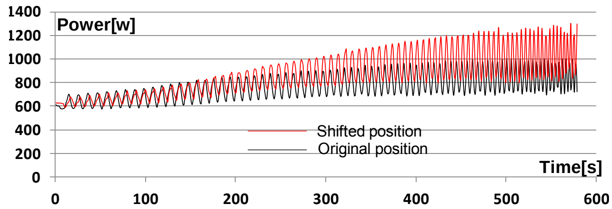


Figure 8: Effect of the sheet positioning on the power profile for the DC01 steel test

Table 5 reports the additional energy due to position changing. For DC01, the material tested with the highest tensile strength, the additional energy amounts to 9 %. As a consequence, the effect of the material on the power demand result is amplified compared to the influence the material had in the original position. Again in the case of the DC-01 steel the material contribution on the total energy thus rises up to 39%.

Table 5: Results obtained for the shifted position

Material	Energy [kJ]	Average power [W]	Material contribution share	Additional Energy due to position changing
Air forming	358.5	619		0%
AA-1050	370.7	640	3%	0.5%
AA-5754	434.4	750	21%	6%
DC-01	500.3	864	39%	9%

The results reported above lead to the conclusion that the positioning of the sheet plays a relevant role in terms of energy consumption, and in consequence such parameter has to be optimized from an energy efficiency point of view.

5 CONCLUSIONS

The present study reports an energy consumption analysis, including a power study of Single Point Incremental Forming processes developed on a 6-axes robot. The influence of the most relevant process parameters (e.g. feed rate, step down), the material being formed and the sheet positioning have been analyzed from energy demand point of view. Main conclusion of the first part of the research is that the forming time is the dominant factor in the energy demand of SPIF processes. Such conclusion was drawn by analyzing the production mode time share as well as the energy demand for four different parameter combinations.

These statements lead to the conclusion that the first strategy to reduce the energy demand of SPIF processes is reducing the forming time by optimizing the tool path and working at the highest admissible feed rates.

In order to better understand the parameters affecting the variable part of the energy demand, also the contribution of the material and the positioning of the sheet on the power demand have been analyzed. Three different materials, characterized by different strength grades, were formed by the SPIF process and the energy demand was analyzed. It was observed that at the increasing of the material strength the power/energy demands considerably increase, so the material contribution share on the total energy demand account for up to 22% for the strongest considered material.

The sheet positioning is another parameter which , significantly affects the power/energy demand. As matter of fact to form the strongest material in the considered shifted position an extra energy requirement of 9% was observed. Summing up, the material being formed has to be considered for an accurate energy prediction, and since the positioning of the sheet strongly affects the energy demand; such parameter should also be optimized to improve the energy efficiency of the process. Such assessments lead to the conclusion that the energy demand for robot supported SPIF processes is characterized by a constant amount and a variable one. The constant part concerns the air forming energy demand, the variable part instead is affected by the parameters determining the force necessary to form the sheet (material, drawing angle, thickness, etc.) and by the sheet positioning.

6 ACKNOWLEDGMENTS

The authors acknowledge the financial support from FWO (Research Foundation – Flanders), under the scheme of Pegasus/Marie Curie, as well as the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) through its PhD grant No. 091232 and the O&O EnHiPro project (Project No. 090999).

7 REFERENCES

[1] Duflou, J.R., Sutherland, J., Dornfeld, D., Herrmann, C. Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012,. Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals - Manufacturing Technology, 61/2: 587-609.

[2] Gutowski, T., Dahmus, J., Thiriez, A., 2006, Electrical Energy Requirements for Manufacturing Processes; Proc. 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium.

[3] Diaz, N., Redelsheimer, E., Dornfeld D. 2011. Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use; *Proc. 18th CIRP International Conference on Life Cycle Engineering*, Braunschweig, Germany.

[4] Kara, S., Li, W., 2011, Unit process energy consumption models for material removal processes, *CIRP Annals - Manufacturing Technology,* 60: 37-40.

[5] Oliveira, M., Santos, J., Almeida, F., Reis, A., Pereira, J. P., Rocha, A., 2011, Impact of Laser-based Technologies in the Energy-Consumption of Metal Cutters: Comparison between commercially available System, *Key Engineering Materials,* 473: 809-815.

[6] Thiriez, A., Gutowski T., 2006, An Environmental Analysis of Injection Molding: *Proc. IEEE Symp. on Electronics and the Environment*, Scottsdale.

[7] Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Rosamond E., Hague R., 2012, Transparency Built-in Energy Consumption and Cost Estimation for Additive Manufacturing, Journal of Industrial Ecology. DOI: 10.1111/j.1530-9290.2012.00512.x.

[8] CO2PE! – Cooperative Effort on Process Emissions in Manufacturing, last visited 06/03/13, www.co2pe.org

[9] Kellens, K., Dewulf, W., Overcash, M., Hauschild, M.Z., Duflou J.R., 2012, Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! initiative (cooperative efforton process emissions in manufacturing). Part 1: Methodology description. Int. J. Life Cycle Assessment, 17: 69-78.

[10] Bay, N., Azushima, A., Groche, P., Ishibashi, I., Merklein M., Morishita M., Nakamura T., Schmid S., Yoshida M.,2012. Environmentally benign tribo-systems for metal forming, CIRP Annals - Manufacturing Technology 59: 760–780.

[11] Santos, J. P., Oliveira, M., Almeida, F. G., Pereira, J. P. Reis, A., 2011, Improving the environmental performance of machine-tools: influence of technology andthroughput on the electrical energy consumption of a press-brake,J. Clean. Prod., 19: 356-364.

[12] Kellens, K., Dewulf, W., Duflou, J. R., 2011, Environmental Analysis of the Air Bending Process. Proc. 14th International ESAFORM Conference on Material Forming , ed. G. Menary, Belfast, Ireland, 1353:1650-1655.

[13] Duflou, J.R., Kellens, K., Renaldi, Dewulf, W., 2011,Keynote of SheMet, Key Eng. Materials,473: 21-26.

[14] Ingarao G., Di Lorenzo R., Micari F., 2011, Sustainability issues in sheet metal forming processes an overview, J. Clean. Prod,19: 337-347.

[15] Kim, Y.H., Park, J.J., 2002, Effect of process parameters on formability in incremental forming of sheet metal, J. Mater. Process. Technol.,130/131: 42–46.

[16] Duflou J., Callebaut B., Verbert J., De Baerdemaeker H., 2007, Laser assisted incremental forming: formability and accuracy improvement, CIRP Ann. Manuf. Technol., 56/1 : 273–276.

[17] Ambrogio G., Filice L., Manco G.L., 2008, Warm incremental forming of magnesium alloy AZ31, CIRP Ann. Manuf. Technol., 57/1: 257–260.

[18] Fan G., Sun F., Meng X., Gao L., Tong G., 2010, Electric hot incremental forming of Ti-6Al-4V titanium sheet, Int. J. Adv. Manuf. Technol., 49: 941–947.

[19] Ingarao, G. Ambrogio, F. Gagliardi, R. Di Lorenzo, 2012, A sustainability point of view on sheet metal forming operations: material wasting and energy consumption in incremental forming and stamping processes, J. Clean. Prod. 29-30: 255-268.

[20] Dittrich, M. A., Gutowski, T., G, Cao, J., Roth, J.T Xia, Z. C., Kiridena, V., Ren, F., Henning, H., 2012, Exergy analysis of incremental sheet forming, Prod. Eng. Res. Devel., 6: 169-177.

[21] Ingarao, G., Kellens, K., Behera, A. K. Vanhove, H., Ambrogio, G., Duflou, R. J., 2013, Electric energy consumption analysis of SPIF processes, Key Eng. Materials, 549: 547-553.

4.3 Interdependencies between energy productivity and target figures of lean production systems

P. Schnellbach, G. Reinhart

Fraunhofer IWU – Project Group Resource-efficient Mechatronic Processing Machines, Augsburg, Germany

Abstract

Energy productivity will be a significant competitive advantage for manufacturing companies in future. Therefore, a methodical approach is necessary to identify potential in manufacturing and reduce energy waste. In order to develop this approach, it is obligatory to consider interdependencies to established production systems. Starting with Toyota, car manufacturers were pioneers for the implementation of Lean Production Systems (LPS). Their production processes are measured by LPS target figures like quality or through-put time. Efforts to raise energy productivity can cause impacts on existing production processes and therefore result in interdependencies with LPS target figures. The methodology presented in this paper helps to increase energy productivity under consideration of these interdependencies. The so called House of Energy Productivity is introduced as one important part of the methodology.

Keywords:

Lean Production, Energy Productivity

1 INTRODUCTION

Coming from the background of a worldwide shortage of resources, a wise consumption of energy has become a main issue for governments as well as manufacturing companies. With 31 % of primary energy use, manufactures are one main consumer of energy [1]. That high proportion of usage leads to a certain responsibility for energy waste reduction. Important drivers like rising energy prices, new environmental regulations with their associated costs for CO_2 emissions and changing customers' behavior with regard to green products must be considered by manufacturers in the short run. An efficient and effective use of energy can make a high contribution towards energy waste reduction [2]. Besides other resources, energy in manufacturing is therefore an important field for both science and industry.

Starting with Toyota, car manufacturers were pioneers for the implementation of Lean Production Systems (LPS) in the last decades. By doing so, they succeeded in improving target figures like lead time, quality and cost [3]. Reduction of energy waste in manufacturing was not of great concern at that time and is therefore not described as a part of LPS [4]. Already existing and established LPS structures in turn can help integrating energy productivity aspects in manufacturing companies sustainably [5], [6]. However, by implementing a structured proceeding to reduce energy waste, possible interdependencies to LPS target figures have to be considered. Otherwise the combination of lean and green measures can have unexpected impacts on production [7].

Therefore, the Project Group Resource-efficient Mechatronic Processing Machines (RMV) of Fraunhofer IWU started to develop a methodical approach to increase energy productivity in car manufacturing while considering interdependencies to LPS target figures. This paper presents the so called House of Energy Productivity (HoEP), which is part of that methodical approach. The paper starts with a definition of energy productivity in manufacturing and a description of important target figures in LPS. Guidelines to increase energy productivity are derived from the state of the art literature and integrated in the HoEP. The guideline example *recuperation* shows the usage of the HoEP and reveals direct impacts of measures on electrical power and time.

2 ENERGY PRODUCTIVITY AND TARGET FIGURES IN LEAN PRODUCTION SYSTEMS

2.1 Definition of energy productivity in manufacturing

The term energy productivity is often used to measure the performance of national economies quantified as the gross domestic product (GDP) divided by the nation's energy consumption [8], [9]. In manufacturing the term energy efficiency is more common, generally measured as the useful output of a process divided by the energy input [8], [10]. Although the quantification in both cases is output divided by input, and both terms are often used as synonyms, there are reasons to make a difference. [11] define the term *productivity* as social concept and as an *attitude of mind* strongly combined with the continuous improvement process. Productivity tries to improve already existing things continuously in order to become better every day. [12] states that productivity is commonly defined as efficiency (outputs over inputs) plus effectiveness (outputs relative to a standard or goal). By combining both terms, productivity can be defined as [11]:

Productivity = Efficiency + Effectiveness
= "Doing the things right" + "Doing the right things" (1)

These perceptions can be translated to energy productivity in manufacturing as well:

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

Energy productivity is hereby seen as an attitude of mind to improve the ratio of useful output divided by the energy input. On company level it is measured by output or value added e. g. in form of sales divided by the energy input e. g. in form of total energy cost [13]. On shop floor level energy intensity (the inversion of energy productivity) is measured as the energy use divided by a unit of industrial output, e. g. kWh/car [1], [2], [9]. Energy intensity is used on shop floor level in order to make energy demand more tangible for workers.

With these measurements on company as well as on shop floor level, energy effectiveness is not considered so far. Effectiveness is defined as a measurement of outputs compared with goals [12]. Correspondingly, it can be translated as *Doing the right things* as mentioned before [11]. In case of energy productivity in car manufacturing, the *right things* are considered as measures to reduce energy waste either without negative impact, or with positive impact on existing manufacturing structures. Especially in car manufacturers' industry these structures are strongly designed by LPS [14]. The overall performance of LPS is reflected in target figures like quality or lead time [15].

To sum up, energy productivity in manufacturing is defined as an attitude of mind to reduce energy waste continuously through energy waste reducing measures considering the impact on LPS target figures.

2.2 Target figures in Lean Production Systems

LPS are defined as "enterprise-specific compilations of rules, standards, methods and tools, as well as the appropriate underlying philosophy and culture for the comprehensive and sustainable design of production" [16]. They consist of principles, methods and tools and have their origin in the Toyota Production System (TPS). TPS was developed by Toyota in Japan in the middle of 20th century. In 1990 it was revealed through a study published by the International Motor Vehicle Program (IMVP) of Massachusetts Institute of Technology (MIT). The study presented a Japanese manufacturing concept, which was superior to the manufacturing concepts of American and European car manufacturers. It became popular as *Lean Production* [3].

Instead of going for *make-to-stock*, Toyota implemented the principle of *Just-in-Time* as one pillar of the TPS, which is often shown in form of a house. The second pillar was called *Jidoka*, which is also known as *autonomation* – the ability for production machines to stop autonomously in case of manufacturing defects. The basement of the TPS house was built by the continuous improvement process (CIP), also known as *Kaizen*, which was concentrated on eliminating waste by continuous step-by-step improvements [17]. In order to do so, Toyota defined seven types of waste like over-production, inventory or waiting. Different lean methods like *Kanban* or *Poka Yoka* helped to implement the principles of the TPS in production [3], [18]. After the publication of the IMVP study, American and European car manufacturers started to adapt the TPS and implemented it in their own company [14]. Today these production systems are generally known under the term *Lean Production System* (LPS) [4].

After measuring the performance of manufacturing usually with the target figure cost in the past, several other target figures are common in LPS today [15], [19]. From a state of the art research, four important target figures have been chosen to measure the performance of the LPS in car manufacturing and to visualize the impact of energy productivity on LPS. These four target figures are flexibility, lead-time, productivity and quality. Since every mentioned target figure can be derived monetarily, they have an indirect impact on cost. Therefore, cost is not considered as separate target figure in the presented methodology [20]. Table 1 shows the quantification of the chosen target figures.

Target Figure	Quantification
flexibility F	$F = \frac{\# res}{\# var} \times \frac{wt}{(pb \times pt) + ct}$ with # res: number of same resources # var: number of variants wt: daily working time pb: average production batch pt: processing time ct: changeover time
lead time L	L [time unit] = time of distribution − begin of processing
productivity P	$P\,[\%] = \frac{\text{production output}}{\text{maximum production output}} \times 100$
quality Q	$Q\,[\%] = \frac{\text{zero defects products}}{\text{production output}} \times 100$

Table 1: Quantification of target figures, adapted from [20].

In order to reduce energy waste in manufacturing considering interdependencies on LPS target figures, an analysis to expose these interdependencies is necessary.

2.3 Interdependencies between energy productivity and LPS target figures

Interdependencies between measures to increase energy productivity and LPS target figures are obvious as the following example points out. An oven used for a drying process would not utilize its full capacity in order to create a single-piece flow. Coming from an energetic perspective, the energy intensity of the process could be reduced by changing the single-piece flow principle into a batch production. By doing so, the full capacity of the oven could be used and less energy would be wasted to dry the products. On the other side, a change from single-piece flow to a batch production could result in a longer lead time (Figure 1).

Besides the impact on lead time, there are possible impacts on other target figures, too. The simple example from Figure 1 shows the requirement for an intense analysis of interdependencies on LPS target figures. Therefore, it is necessary to develop a methodology, which

- helps to identify energy productivity potential in a defined manufacturing area,
- offers concrete measures derived from guidelines and adjusting levers to increase energy productivity,

- considers interdependencies between energy productivity measures and LPS target figures and
- gives recommendations to decide, which measures should be implemented or not.

Every bullet point describes one part of the whole methodology. The second part in order is the HoEP, which is explained in this paper.

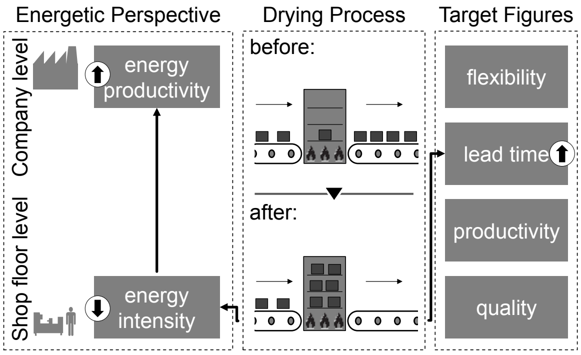


Figure 1: Interdependencies between energy productivity and lead time through the change of a drying process.

3 HOUSE OF ENERGY PRODUCTIVITY

The HoEP (Figure 2) is one important part of the methodology. It helps to derive concrete measures to improve energy productivity respectively to reduce energy intensity. The preliminary work to build up the HoEP, its important components and its application are described in the following chapters.

3.1 Development approach and preliminary work

In order to develop the above mentioned methodology, general possibilities to increase energy productivity have been investigated in a preliminary work. Therefore, a 3-step approach has been created. First step is the definition of guidelines for possible energy productivity potential. In a second step, the guidelines lead to adjusting levers, which can be classified into an energy productivity portfolio to visualize possible impacts. Guidelines and adjusting levers build important components of the HoEP and help to generate concrete quantifiable measures to reduce energy waste in a third step.

3.2 Components of the House of Energy Productivity

Energy productivity guidelines are an important component of the HoEP. While giving orientation to identify energy waste potential on an abstract level, they are comparable to the seven types of waste in LPS [16], [18]. The procedure to define the guidelines is visualized schematically in Figure 3. At first the existing literature was analyzed for the state of the art guidelines. Several other terms like *general approaches* or *energy efficiency principles* are used in the same sense and were considered during the research as well. As a result, 15 different references with overall 159 guidelines were identified. Next step was a reduction by eliminating those, who didn't fit one of the following criteria.

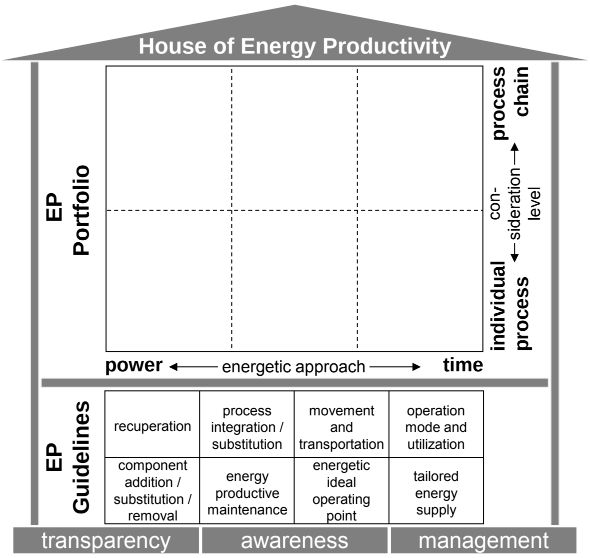


Figure 2: House of Energy Productivity.

In terms of energy economics, only guidelines which handled net energy were considered [21]. Furthermore, the guidelines had to be applicable to car manufacturing industry. Besides, only guidelines which referred to operating phase and therefore to the CIP during product life cycle were considered. The last elimination criterion was related to the guideline's energy cost leverage. The two charges, which can be affected directly in manufacturing, are the energy charge (price based on the energy consumed within a certain time frame expressed in kWh) and the power charge (price based on the peak expressed in KW) [22]. As the possible impact on peak loads is limited on a shop floor level, for the developed methodology the energy charge was considered as cost leverage exclusively. Guidelines, which address peak loads, should be considered in a companywide peak load management, which is not part of the developed methodology. Furthermore, some guidelines fit the criteria, but would not lead to concrete quantifiable measures. Such guidelines refer to transparency, awareness and managerial structures to support the energy productivity improvement process. They were separated from the rest and summarized within one basic principle building the basement of the HoEP.

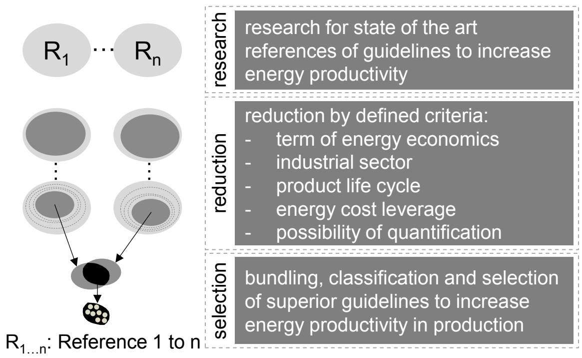


Figure 3: Procedure to define energy productivity guidelines, adapted from [23].

After the step of reduction, the 66 remaining guidelines were bundled and classified to eight superior guidelines which are shown in Figure 4.

recuperation	process integration / substitution	movement and transportation	operation mode and utilization
component addition / substitution / removal	energy productive maintenance	energetic ideal operating point	tailored energy supply

Figure 4: Energy productivity guidelines.

From every guideline, several adjusting levers can be derived. They differ from the guidelines in their level of detail. Considering the elimination criteria mentioned above and using the guidelines as orientation, adjusting levers are possibilities to increase energy productivity, while showing their direct impact on energy consumption. In order to do so, an energy productivity portfolio was designed with two dimensions (Figure 6).

On the ordinate, the consideration level is shown. The differentiation is between an individual production process, which consists of a certain technology and the manufacturing equipment [24], and a process chain, which consists of different individual processes. Adjusting levers, which have impact on one individual production process only, are positioned in the lower area of the portfolio. Levers, which affect more than one process, are positioned in the upper area.

The abscissa shows the energetic approach of the levers. Generally energy is quantified by the multiplication of electrical power and time [10], [25]. Therefore, every energy productivity measure, which is generated out of an adjusting lever, either has an impact on electrical power (left area of the portfolio), on time (right area of the portfolio), or on both (medium area of the portfolio). As LPS target figures are mainly time driven (Table 1), a position on the right area of the portfolio results in a higher impact level.

Every impact on electrical power causes a change in efficiency η defined as ratio obtained from target energy flows supplied and energy flows used in an individual process or a process chain in the stationary state [21]. Every impact on time can be directly quantified with help of production time recording models, such as the occupation time model of [26]. Therefore, every adjusting lever must be assignable to one of the six areas of the portfolio to reveal its direct impact on energy. From the state of the art a defined number of adjusting levers can be deviated and documented. The procedure for the identification of the levers is presented exemplarily in the next chapter. With the knowledge of their impact on energy, the adjusting levers can be used to identify concrete measures in a defined manufacturing area.

The energy productivity portfolio, the guideline table and the basic principle (transparency, awareness and management) are the important components to build up the HoEP (Figure 2). The application of the HoEP is exemplified with the help of the guideline *recuperation*.

3.3 Exemplary application of the HoEP with the guideline *recuperation*

The origin of the term *recuperation* is the Latin verb *recuperare*, which means *recover* or *regain*. In the HoEP, the guideline *recuperation* is defined as general term for the approaches recovery, insulation and storage of energy. Possible measures, which can be found in literature, are

- recovery of braking energy e. g. from electric actuation [27],
- use of waste heat, resulting from the production process [25], [28],
- storage of energy loss for a later utilization on demand [28] and
- sustainable insulation of wiring, pipes and machine parts in order to avoid energy loss in production processes and during energy transfer [25].

The sustainable insulation must be distinguished from continuous actions to identify and reduce leakage losses e. g. from compressed air. Such actions are covered by the guideline *energy productive maintenance*.

Considering the elimination criteria, the possibilities for *recuperation* in production phase are restricted. The later enabling of a machining center to recover braking energy during production phase doesn't amortize and should be considered in production planning phase instead [27]. From the state of the art literature, it comes to the two possible adjusting levers heat recovery and sustainable insulation. Storage of energy loss is seen as a variation of heat recovery. For sustainable insulation the position on the ordinate of the portfolio depends on whether a single production process (e. g. a single machine center or parts of it) is affected (lower portfolio area), or a whole distribution network with several processes is affected by the insulation (upper portfolio area). In case of heat recovery, the ordinate position depends on whether the gained energy is used within the same process, where it was recovered (primary), or in another process (secondary) [29]. Primary use is positioned in the lower portfolio area, whereas secondary use belongs to the upper portfolio area.

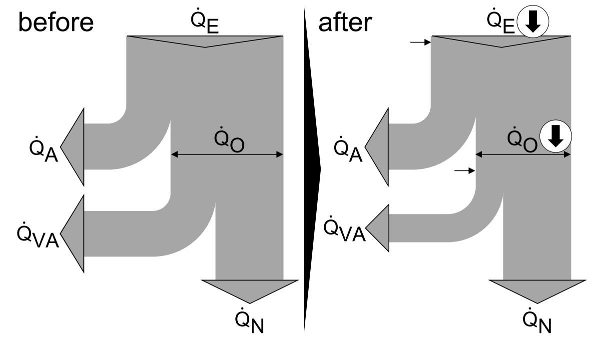
In order to determine the portfolio positions on the abscissa, possible changes in efficiencies of stationary states are proved. The technical term energy efficiency η_{en} is the sum of the thermal efficiency η_{th} and the machinery-specific efficiency η_{at}.

$$\eta_{en} = \eta_{th} + \eta_{at} \tag{2}$$

The thermal efficiency η_{th} is calculated by the ratio of the machinery-specific input power $\dot{Q}_O$ and the input power $\dot{Q}_E$. The machinery-specific efficiency quantifies the ratio of the output power $\dot{Q}_N$ and the machinery-specific input power $\dot{Q}_O$ [29].

$$\eta_{en} = \frac{\dot{Q}_O}{\dot{Q}_E} + \frac{\dot{Q}_N}{\dot{Q}_O} \tag{3}$$

Figure 5 exemplifies the impact of an insulation of a drying process to reduce the indirect power loss $\dot{Q}_{VA}$ in terms of a wall loss. The insulation causes a reduction of $\dot{Q}_O$ and thus of $\dot{Q}_E$. With constant $\dot{Q}_N$ the machinery-specific efficiency η_{at} grows. In case of *recuperation*, both heat recovery and sustainable insulation have an impact on energy efficiency η_{en} and accordingly on electrical power.



with

$\dot{Q}_E$: input energy per time (input power)

$\dot{Q}_A$: direct power loss during generation of useful energy

$\dot{Q}_O$: machinery-specific input energy per time (machinery-specific input power)

$\dot{Q}_{VA}$: indirect power loss, e. g. cooling water enthalpy, wall loss, …

$\dot{Q}_N$: output energy per time (output power)

Figure 5: Impact of an insulation of a drying process on the energy efficiency η_{en}, adapted from [29].

Hence, none adjusting lever can be positioned in the right area of the portfolio, where only time is affected. By proving the impact of recovery and insulation on time e. g. with an occupation time model [26], it becomes clear, that there are adjusting levers, which cause impacts on both electrical power and time. A heat recovery which is used to reduce the ramp-up time of a drying process can be given as example.

With this information, eight adjusting levers can be deviated from the guideline *recuperation* and positioned into the energy productivity portfolio (Figure 6).

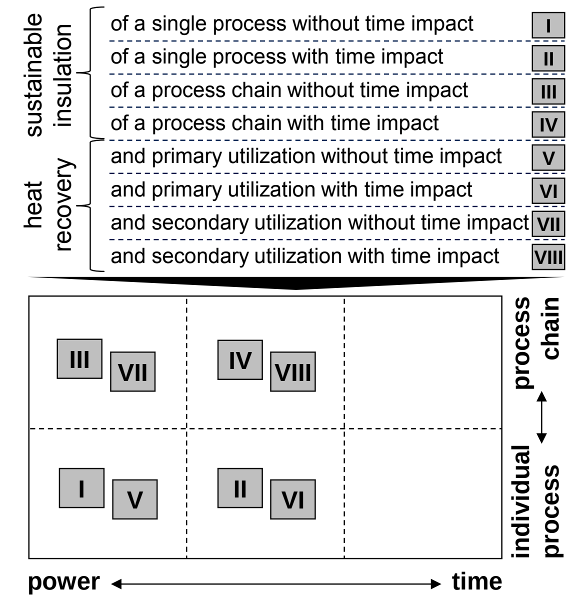


Figure 6: *recuperation* adjusting levers positioned into the energy productivity portfolio.

Completed by the adjusting levers of the other seven guidelines, the portfolio helps to identify concrete measures and at the same time makes their direct impacts on electrical power and time comprehensible. Thereby, the necessary fundament is established to identify interdependencies to LPS target figures.

4 CONCLUSION AND OUTLOOK

After pointing out the significance to reduce energy waste in manufacturing, the paper defines the term energy productivity as an attitude of mind, which combines efficiency and effectiveness, to reduce energy waste continuously through measures considering impacts on important LPS target figures. Therefore, a four step methodology was developed.

One important part of the methodology is the HoEP, which helps to generate concrete energy productivity measures through a 3-step approach. By means of revealing general possibilities to increase energy productivity, eight guidelines were derived from state of the art literature. With the guideline *recuperation*, the procedure to position adjusting levers into an energy productivity portfolio was exemplified. The portfolio defined the direct impact on electrical power and time.

Starting from the HoEP, further parts will be developed to complete the whole methodology. Upstream to the HoEP and first part on order is an adapted version of the energy value stream [13], which delivers the necessary energetic transparency to reveal energy productivity potential. Downstream, the third part is a standardized method to visualize and quantify existing interdependencies to LPS target figures, which will be identified from the fundament of deviated adjusting levers. Therefore, possibilities to visualize and quantify such interdependencies are evaluated. One possibility to do so will be the system dynamics approach, which is generally used to simulate effects from defined actions in complex systems with help of qualitative and quantitative models [30]. The final part of the methodology will be a standard procedure to give recommendations for the realization of energy productivity measures.

5 REFERENCES

[1] International Energy Agency (IEA), 2007, Tracking Industrial Energy Efficiency and CO_2 Emissions, retrieved from http://www.iea.org/publications/freepublications/publication/tracking_emissions.pdf

[2] Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M., Ernst, F. O., 2011, Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature, Journal of Cleaner Production, Vol. 19, 667-679.

[3] Womack, J. P., Jones, D. T., Roos, D., 1991, The machine that changed the world: The story of Lean Production, Harper Perennial, New York.

[4] The Association of German Engineers (VDI), 2012, Guideline 2870-1 – Lean production systems – Basic principles, introduction and review, Beuth, Berlin, Germany.

[5] Dombrowski, U., Mielke, T., Schulze, S., 2011, Lean Production Systems as a framework for Sustainable Manufacturing, 9th CIRP Conference on Sustainable Manufacturing, St. Petersburg, Russia.

[6] Bergmiller, G. G., McWright, P. R., 2009, Are Lean and green programs synergetic? Proceedings of the Industrial Engineering Research Conference, Miami, USA.

[7] Yang, M. G., Hong, P., Modi, S. B., 2011, Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing firms, International Journal of Production Economics, Vol. 129, 251-261.

[8] Patterson, M. G., 1996, What is energy efficiency ? – Concepts, indicators and methodical issues, Energy Policy, Vol. 24, No. 5, 377-390.

[9] Wang, C., 2006, Decomposing energy productivity change: A distance function approach, Energy, Vol. 32, No. 8, 1326-1333.

[10] Thiede, S., 2012, Energy Efficiency in Manufacturing Systems, Springer, Heidelberg, Germany.

[11] Roghanian, P. Rasli, A., Gheysari, H., 2012, Productivity Through Effectiveness and Efficiency in the Banking Industry, Procedia – Social and Behavioral Sciences, Vol. 40, 550-556.

[12] Pritchard, R. D., 2004, Productivity, Encyclopedia of Applied Psychology, Vol. 3, 121-125.

[13] Reinhart, G., Karl, F., Krebs, P., Reinhardt, S., 2010, Energy Value Stream – Method for integrated increase of energy productivity, Zeitschrift für wirtschaftlichen Fabrikbetrieb (ZWF), Vol. 105, No. 10, 870-875.

[14] Holweg, M., 2007, The genealogy of lean production, Journal of Operations Management, Vol. 25, 420-437.

[15] Peter, K., Lanza, G., 2011, Company-specific quantitative evaluation of lean production methods, Production Engineering – Research and Development, Vol. 5, 81-87.

[16] Dombrowski, U., Schmidt, S., 2008, Framework for the Planning and Control of Lean Production System Implementation, International Journal of Agile Manufacturing Systems, Vol. 11, 39-45.

[17] Imai, M., 1986, Kaizen – the key to Japan's competitive success, Random House, New York, USA.

[18] Ohno, T., 1998, The Toyota Production System: Beyond Large-Scale Production, Productivity Press, Portland, USA.

[19] Hon, K. K. B., 2005, Performance and Evaluation of Manufacturing Systems, Annals of CIRP, Vol. 52, No. 2, 675-690.

[20] Peter, K., 2009, Bewertung und Optimierung der Effektivität von Lean Methoden in der Kleinserienproduktion, Shaker, Aachen, Germany.

[21] The Association of German Engineers (VDI), 2003, Guideline 4661 – Energetic characteristics – Definitions terms and methodology, Beuth, Berlin, Germany.

[22] Pechmann, A., Hackmann, R., Schöler, I., 2012, Measuring and Visualizing Different Energy Sources: A Concept for an Energy Management System, 19th CIRP International Conference on Life Cycle Engineering, Berkeley, USA.

[23] Ullmann, G., 2009, Ganzheitliche Produktionssysteme IPH-Methodensammlung, retrieved from http://www.iph-hannover.de/sites/default/files/IPH-Methodensammlung_web.pdf

[24] Fallböhmer, M., 2000, Generieren alternativer Technologieketten in frühen Phasen der Produktentwicklung, Shaker, Aachen, Germany.

[25] Müller, E., Engelmann, J., Löffler, T., Strauch, J., 2009, Energieeffiziente Fabriken planen und betreiben, Springer, Berlin, Germany.

[26] German Association for work design, industrial organization and company development (REFA), 1993, Lexikon der Betriebsorganisation, Carl-Hanser, Munich, Germany.

[27] Prognos, 2007, Potenziale für Energieeinsparung und Energieeffizienz im Lichte aktueller Preisentwicklungen, retrieved from http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/studie-prognosenergieeinsparung,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf

[28] Erlach, K., Westkämper, E., 2009, Energiewertstrom, Fraunhofer, Stuttgart, Germany.

[29] Schieferdecker, B., Fuenfgeld, C., Bonneschky, A., 2006, Energiemanagement-Tools, Springer, Berlin, Germany.

[30] Karnopp, D. C., Margolis, D. L., Rosenberg, R. C., 1990, System Dynamics: A unified Approach, Whiley-Intersience, New York, USA.

4.4 Measurement strategy for a production-related multi-scale inspection of formed work pieces

A. Loderer, B. Galovskyi, W. Hartmann, T. Hausotte[1]

[1] Institute of Manufacturing Metrology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany

Abstract

The technology of sheet-bulk metal forming provides numerous advantages in the field of manufacturing. Work pieces with filigree and complex structures can be formed by only a few forming steps. To ensure a sustainable and effective production, the forming process has to be controlled by a production-related measurement system. A measurement system, which meets the high requirements of a forming process like a short measuring time, a high measuring point density and the ability to measure different features at the same time, is a multi-scale fringe projection system with multiple sensors of different resolutions. However, an adapted definition of a measurement strategy is necessary in order to enable a rapid conformity decision of the manufactured work piece based on the evaluated measurement data and thus to be able to inspect as many work pieces as possible. It allows to correct the manufacturing during a primary forming process and to assure a sustainable forming process.

Keywords:

Fringe projection; multi-scale measurement; sheet-bulk metal forming

1 INTRODUCTION

In times of increasing raw material costs, saving resources provides not only economical and sustainable advantages but also monetary benefits. Especially by improving production technologies, the reduction of the consumption of raw materials is possible. The aim is on the one hand, to generate the product with as less material and energy as possible. On the other hand, the product itself should be as light but also stabile as possible. In many cases, these demands could only be partially met by the current production processes. Indeed, they are able to deliver lightweight structures and products, but only at high cost. Therefore, this state of the art motivated the search for a new high performance forming method. The development of the sheet-bulk metal forming enables the production of high quality sheet metal components with highly loaded functional elements [1].

With the sheet-bulk metal forming technology the production of complex work pieces in only a few forming steps is possible with a minimum of required material. The increasing number of integrated function elements and the reduction of required material and process steps, which is attended by the reduction of energy consumption, is possible by an three dimensional material flow. Due to this new method filigree structures as well as geometric unequal features can be produced in only one step [1]. In order to research the new technology and their possibilities, the transregional collaborative research center (Transregio) 73 as a joint research initiative was found [2].

But a sustainable production is not only characterized by a reduction of material requisition and energy consumption [3]. At the same time, the reduction of wastage is important task. This requires a control of the produced work pieces [4]. By evaluating the work piece's quality, for example the geometrical dimensions, control variables can be derived and thereby the process could be regulated. The high output of work pieces and their complex structure generate high requirements on the measuring technology. Because of the fact that all surface features are formed in only one step, all of the features have to be controlled nearly at the same time. That means a holistic inspection has to be arranged in a way that features of all sizes are measured by measuring systems which accuracies are precise enough and measurement areas are big enough [5]. These high demands could be meet best with the optical measurement technology. This measurement method is contactless and enables complete detection of the work piece's surface in a very short time [6]. Besides laser scanning systems, fringe projection systems are already in use for production-related or even in-line measurements [7]. Due to the different scale of the work piece feature of sheet-bulk metal forming parts, a combination of systems with different resolutions is needed. To guarantee the appropriate accuracy for each work piece feature multiple fringe projection sensors with different measurement areas and accuracies has to be arranged. Thus a multi-scale measurement is possible [5].

In order to guarantee a high level of sustainability, the wastage has to be as low as possible. Therefore the rate of measured and controlled work pieces has to be as high as possible. The more work pieces are controlled, the faster deviations from the ideal are detected, and the faster variables for the process regulation could be derived. For such measurement not only the measuring systems and sensors have to be optimized and adapted to the sheet-bulk metal forming parts, also the measurement strategy has to be specified. Because of the complex surface and the high output-rate, measurement strategies, which are used in current in-line measuring systems, are not appropriate. The surface structures are in most cases not as complex as on

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

sheet-bulk metal forming parts. Also the output-rate is incommensurable.

In this article an approach for the definition of a measurement strategy for a production-related multi-scale inspection of sheet-bulk metal forming parts is given.

2 CHARACTERISTICS OF SHEET-BULK METAL FORMING

2.1 Demonstrator work piece

In order to demonstrate the performance of the sheet-bulk metal forming a demonstrator work piece was worked out, which is shown in figure 1. For the development of the demonstrator work piece the hoped benefits of the new technology were analyzed. Leading work piece functions are integrated in a smaller number of single components due to the requirement on light weight construction. But also the requirements on the geometry and its accuracy are increasing. Thus technologies like bending or cutting cannot be used for the manufacturing of this new generation of work pieces. Therefore, function features like local tooth systems, carriers and butt straps have to be considered [1].

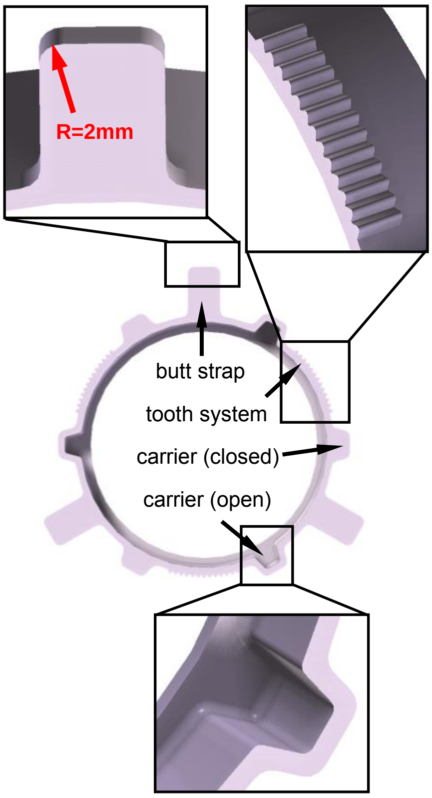


Figure 1: Demonstrator work piece

The tooth system symbolizes a very filigree feature. With a tip circle diameter of merely 0.4 mm, it is the smallest feature of the demonstrator work piece.

Material accumulation should be represented by a closed carrier. Thus the challenge is to transport the required material for a complete molding in the forming tool.

A second carrier in an open design simulates a depth-jump. Here the challenge in the production is to create a constant wall thickness and in addition the small internal diameter, which are in the size of 1 mm.

With a butt strap a possibility is given to check the capability of forming a comparatively long and thin feature. Challenging in this case is keeping the condition of the flatness. Furthermore the diameters of 2 mm at the end of the butt strap have to be molded correct. To guarantee this, a targeted material flow has to set up.

Each of the feature elements can be found three times in the demonstrator work piece.

2.2 Frequently manufacturing defects

Main characteristics of the sheet-bulk metal forming are three-dimensional material flow and material hardening. If these processes are not working proper, it can lead to characteristic defects. The complex geometry of the part features of the demonstrator work piece are designed in order to discover characteristic defects in case of an incorrect working forming process. Figure 2 shows some of the most frequently manufacturing defects.

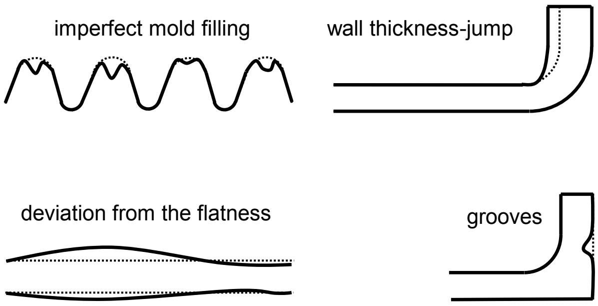


Figure 2: Manufacturing defects

Essential for a correct contour molding is a correct mold filling of the mold cavity. The material flow has to be set up in such a way, that material is dispersed ideal in the mold cavity and filled this completely [5]. Due to the complex geometry, the material flow has to be adapted to the particular volume of the work piece feature. To give an example, the closed carrier needs more material for a correct mold filling than the tooth system [8].

In contrast, there can be also significant surface deviations. As a consequence of too much available material, there could be variability of the sheet thickness. Equally, material hardening can differ locally. Both cases lead to a deviation of the flatness due to inserted stresses.

The frequently deviations of the ideal surface are essential for the development of a measurement strategy, adapted to the properties of the sheet-bulk metal forming. These deviations have to be detected and evaluated. In order to demonstrate the development of such a measurement strategy, an example of a diameter of 2 mm of a butt strap is used. Besides a simple geometry, a likewise simple defect characterizes this work piece feature as a proper example. In case of an incorrect working forming process, the diameter gets smaller or the roundness deviates clearly.

3 SELECTION OF AN APPROPRIATE MEASURING SYSTEM

3.1 Economic and sustainable importance of measuring systems

The selection of an appropriate measuring system is not only a question of technical requirements. Also economical and sustainable aspects have to be considered. Measurement results are information that is used as a basis for decisions. In case of the sheet-bulk metal forming, the result of the work piece inspection leads to a decision, if a work piece meets the specifications or not and if the variables of the forming process have to be changed. The less reliable the measurement results are, the more wastage is produced. Wastage of course is one kind of dissipation, which should be avoided absolutely. Because of this, when selecting a measurement system as defined by sustainability, the system should be as accurate and as fast as possible [3]. These properties lead to a high inspection rate with accurate results, which lead to a better control of the forming process. And thereby wastage can be avoided. But these properties require a higher monetary effort, which in turn reduces the economic benefit of the sheet-bulk metal forming technology. Therefore, the best agreement between requirements on sustainably and economic benefits have to be made [4].

To avoid a complex analyze, which systems could be the best agreement, the “golden rule of measuring metrology” can help. Georg Berndt developed in 1968 a rule for the selection of measurement systems. Therefore, the measurement uncertainty of the measurement system has to be known. The “golden rule” says, that the measurement uncertainty should be less than a fifth, better less than a tenth, of the tolerance width. If this minimum requirement could be met, it is assured that the measurement results are able to detect work pieces accurate enough. All systems that are conform with the “golden rule” can be consulted for the further selection of an appropriate measurement system [9].

3.2 Technical approach for selecting a measuring system

After preselecting the measurement systems, a clear selection based on a technical approach has to be made. The best measurement system is characterized by the detection of the work piece feature as fast as possible and as accurate as necessary. To test this capability of a measurement system, whether expert knowledge or a test procedure could be used. For the development of a production-related measurement strategy for sheet-bulk metal formed parts only little knowledge exists [5]. The capability of optical measurement procedures, especially fringe projection, was already proofed and is used for work piece inspection [10]. But there are different types of fringe projection systems with different resolutions and measurement areas. Both parameters have to be adequate large respectively accurate to detect a work piece feature holistically. To test this on measurement systems, the work piece feature is compared to an appropriate reference, from which the dimensions are known. If the capability of a measurement system to detect the reference correctly is proofed by repeat measurements, it can be concluded, that also the work piece feature is measured correctly.

This approach should explained by using the complex example of the tooth system. At first a reference for the contour of the tooth system has to be found. The micro-contour standard from the PTB [11] seems to be appropriate for this. It has very filigree surface structures similar to the tooth system and also the diameter on the standard is almost equal to the tip circle diameter. The contour-profile can be seen in figure 3.

Figure 3: PTB micro-contour standard

The advantage of the micro-contour standard is that the dimensions are known very well and the contour is a bit more complex than the original contour. If a measurement system detects the micro-contour standard adequate accurate and fast, it can be concluded that also the tooth system is measured adequately. In the present case of the less complex diameter of the butt strap, the search for a reference is comparatively easy. As reference a segment of 90° of a cylinder a known diameter of 2.005 mm is chosen.

After selecting the reference to test the measurement systems, a selection of appropriate systems has to be done. For a fast and accurate inspection of sheet-bulk metal forming parts, fringe projection systems are already in use. After comparing parameters like resolution and measurement area, two different fringe projection systems are selected for the further investigations. System 1 has a resolution of 17 µm (lateral) and 1.0 µm (vertical) with a measurement volume of 13 x 8 x 3 mm³. System 2 has a resolution of 5 µm (lateral) and 0.3 µm (vertical) with a measurement volume of 4.4 x 2.8 x 1 mm³. For the detection of the reference as well as of the work piece feature, that has a dimension of 2 mm and, related to the tolerance DIN 2768m, a tolerance width of plus/minus 0.2 mm, both systems are appropriate. Also considered for the selection of measurement systems should be the “golden rule of measuring metrology”. In our case the tolerance width is 0.4 mm. That leads us to a minimum measurement uncertainty of 80 µm. Better would be a measurement uncertainty of 40 µm.

With both measurement systems 40 repeat measurements on the reference are done. Contrary to a measuring system analysis, the measurements are not done by different operators. Instead of this, the measurements are done under almost production-related conditions. Thereby one operator sets up the measurement system and the reference once and starts the measuring process again and again. This procedure is similar to an automatically work piece inspection.

For the evaluation of the results, normally in addition to the measuring values also the measuring cycle time is recorded. It reaches form the beginning of the measurement until the end of the evaluation. But both considered fringe projection systems do not have an automatically evaluation implemented yet. Because of this, the measuring cycle time is not recorded and considered for the further investigations.

For a fast and reliable selection of an appropriate measurement system, simple parameters can be used. The measurement results of repeat measurements of an ideal measurement system are not normally distributed, but are always the same value. Because of this, additional mathematical limitations have to be observed. It is not possible to calculate parameters like the standard deviation

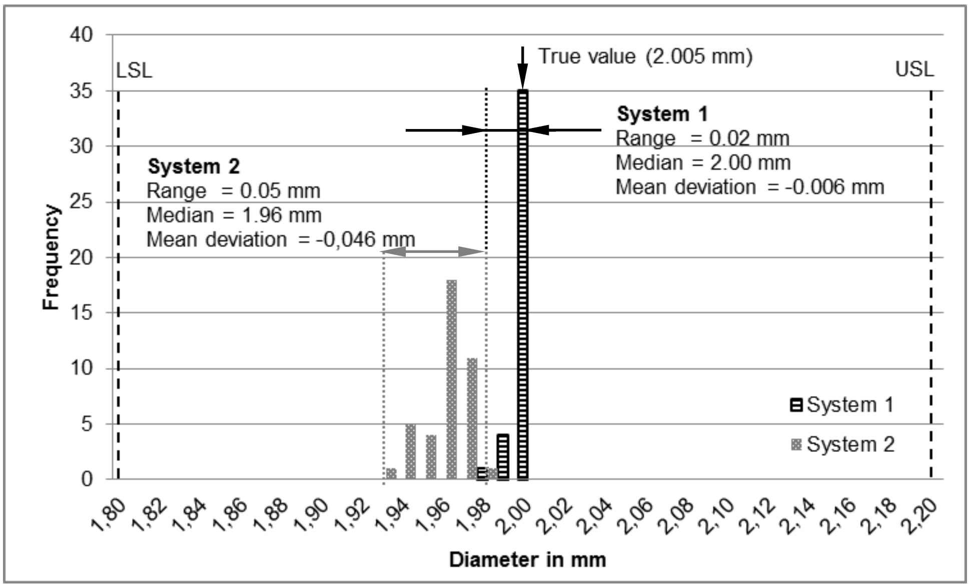


Figure 4: Measurement results and parameters

or the measurement capability index on a simple way. Hence, for the comparison of the measurement systems only simple parameters are considered. Firstly, the range of the measurement results is calculated. This parameter is the result of the difference between the highest and the lowest value. The parameter shows how good a measurement system is able to reproduce a measurement result under prevailing conditions. Next, the differences between each measurement result and the true value for the reference are calculated. From this follows how far a measurement result is away from the true value. The mean deviation is the result of the average of all differences. As a further parameter, the median is calculated also. This shows which result had been measured most. With these three parameters the more appropriate measurement system for the measurement task can be selected. The here described parameters are shown in figure 4.

4 DEVELOPMENT OF A MEASURMENT STRATEGY

If the parameters range, mean deviation, median and measuring cycle time are known for each work piece feature and measurement system, the measurement strategy can be defined. At first it has to be controlled for each available measurement system, if the minimum requirements of a work piece feature are reached. These minimum requirements have to be defined previously. The range should be at least a fifth of the tolerance width, less than a fifth would be even better. A minimum value for the measuring time depends on the production cycle time and the projected inspection rate. For a production-related inspection, the measuring time should be as close to the cycle time as possible. The higher the inspection-rate, the more work pieces can be controlled and the faster variables for the regulation of the production process can be generated. All measurement systems which reach the minimum requirements are compared directly. Though the intention is to find an appropriate measurement system for each work piece feature and thereby avoid using a system more often than it is available. If a measurement system has to be used more often than it is available, it would mean, that the work piece or the system itself has to be moved or positioned new during the inspection. Thus the measuring cycle time would increase. If the measuring time of a measurement system is significantly shorter than the process cycle time, a new positioning of a measurement system is possible without coming along with any disadvantages.

After selecting a measurement system for each work piece feature, the order of the measurements has to be defined. If possible, the measurements should be done parallel. But if more than one system is connected to the same computer, parallel measurements are not possible. Hence the measurement with the shortest measuring time should begin. If during this measurement a defective work piece feature is detected, the work piece inspection can be stopped and the calculation of variables for the process regulation can be started. Especially for inspections, which takes more time than the production cycle time, it is important, to detect defects as soon as possible. The more time elapses until a defect leads to the calculation of new process regulation variables, the more work pieces with the defect are produced. To increase the efficiency even more, the first measurement should not have the shortest measuring time, but also should inspect the most critical work piece feature. This would assure that the feature with the highest chance for a defect is controlled at first. That way saves important time, which can be used for a precise regulation of the sheet-bulk metal forming process, in order to reduce wastage. And this leads to a better sustainability again.

For a simple control of the selection of the measurement systems, an application based on an Excel-sheet was designed. The application tests, if a measurement system reaches the minimum requirements of a work piece feature and how good the system is in comparison to other measurement systems. With this support, the measurement strategy can be controlled.

In case of the example work piece, the selection of the measurement system is done as follows: The minimum requirement on the ranges, which should be smaller than a fifth of the tolerance width, is reached by both measurement systems. The measuring time is not considered. Due to the small range, the small mean deviation from the true value and the median, which is almost the true value, measurement system 1 is more appropriate for the inspection of the diameter of the butt strap. For the inspection, there are eight sensors of the same type available. Because there are only six diameters on the three butt straps of the demonstrator work piece, each work piece feature can be measured by one system. A movement or repositioning of the work piece or the measurement system is not necessary in this case. A schematic set-up of the measurement systems can be seen in figure 5.

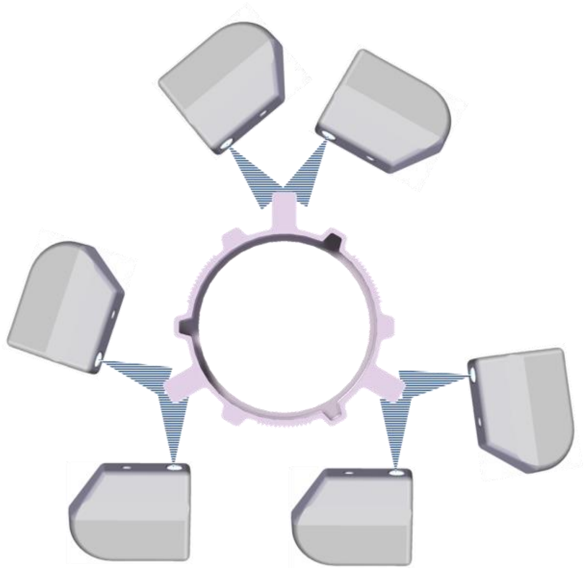


Figure 5: Set-up of the measurement systems

5 SUMMARY AND OUTLOOK

In this article the development of a production-related measurement strategy for the inspection sheet-bulk metal forming parts, in order of a fast and efficient process regulation, was described. For this, the characteristics of the sheet-bulk metal forming were described and their challenges for a production related inspection were explained. An approach for comparing and selecting measurement systems was shown as well as helpful parameters for a fast and simple decision making. The systematic way for selecting a measurement system and strategies for a work piece inspection is expended by the shown approach. Figure 6 shows the approach summarized in a flow chart.

To make the inspection even more efficient and thus increasing the sustainability of the sheet-bulk metal forming, in a next step the selection of an appropriate measurement system will be approximated to a mathematical optimization problem. This can be described and solved by algorithms. Thereby, the selection of a measurement system can not only be checked if the selected system reaches the minimum requirements, but also select the most appropriate system by solving the mathematical equations.

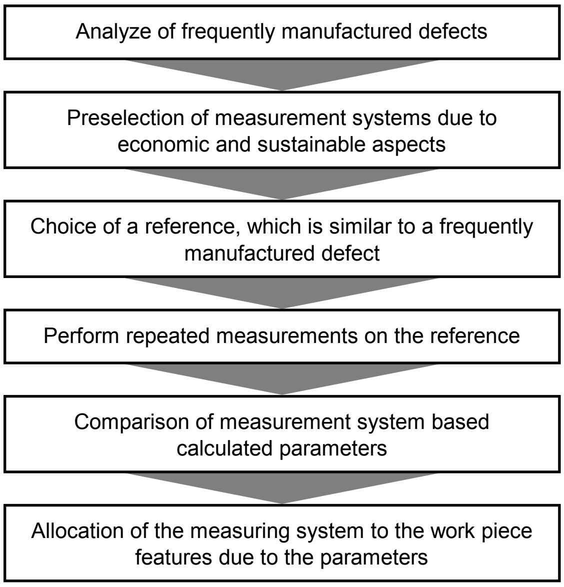


Figure 6: Flow chart

And as a further improvement, the defects during the production could be sorted by their number of appearance. The more often a defect appears, the better would be to start with the measurement of the related work piece feature. Thus it would be possible to detect the most frequently defects at the beginning of an inspection, which leads to a faster process control.

In Order to verify the advantages of the new measurement strategies several case studies have to be worked out and performed. Therefore sheet-bulk metal formed parts with different known defects will be inspected by several measurement system and using different strategies. With the proof of the effectiveness of the measurement strategies, the development of the sheet-bulk metal forming towards an industrial forming technology will be made a sustainably step forward.

6 ACKNOWLEDGMENTS

The underlying research is gratefully funded within the DFG SFB/TR73.

7 REFERENCES

[1] Merklein, M., Allwood, J.M., Behrens, B.-A., Brosius, A., Hagenah, H., Kuzman, K., Mori, K., Tekkaya, A.E., Weckenmann, A., 2012, Bulk forming of sheet metal, Annals of the CIRP - Manufacturing Technology, 61, 725-745.

[2] Schaper, M., Lizunkova, Y., Vucetic, M., Cahyono, T., Hetzner, H., Opel, S., Schneider, T., Koch, J., 2011, Sheet-bulk metal Forming a new process for the production of sheet metal parts with functional components, Metallurgical and Mining Industry, 3/7, 53-58.

[3] Dietlmaier, A., Weckenmann, A., 2011, Economic efficiency in metrology, Proceedings for the 1st International Conference in Quality and Innovation in Engineering and Management, Cluj-Napoca, Romania, March 17-19, 57-62.

[4] Weckenmann, A., Dietlmaier, A., 2009, Risk of erroneous decisions caused by measurement uncertainty, Proceedings for the 9th International Conference on Production Engineering, Design and Control “PEDAC”, Alexandria, Egypt, February 10-12.

[5] Orth, Ch., Kästner, M., Reithmeier, E., Weckenmann, A., Weickmann, J., 2012, Optische Inspektion von Blechmassivumformteilen und –werkzeugen mit feinen Nebenformelementen, Technisches Messen TM, 79/2, 95-101.

[6] Weickmann, J., Liedl, A., Brenner, P.-F., Weckenmann, A., 2009, Reconstruction of a noisy measured sharp edges at thin sheet metal components, FRINGE 09 - The 6th International Workshop on Advanced Optical Metrology, 180-183.

[7] Weckenmann, A., Bernstein, J., 2011, In-line metrology of semi-finished products by the optical bi-sensor-method, 7th Research/Expert Conference “Quality 2011”, Neum, Bosnia-Herzegovina, June 01-04.

[8] Biermann, D., Merklein, M., Engel, U., Tillmann, W., Surmann, T., Hense, R., Herper, J., Koch, J., Krebs, E., Vierzigmann, U., 2011, Umformwerkzeuge in der Blechmassivumformung, Tagungsband zum 1. Erlanger Workshop Blechmassivumformung, Bamberg, Germany.

[9] Berndt, G., Hultzsch, E., Weinhold, H, 1968, Funktionstoleranz und Meßunsicherheit, Wissenschaftliche Zeitschrift der Technischen Universität Dresden, 17/2, 465-471.

[10] Weckenmann, A., Weickmann, J., Hartmann, W., 2008, Multi-component fringe projection sensors: Assistance system for short and robust inspection processes, Proceedings of 2008 NCSL International Workshop and Symposium, August 03-07.

[11] Simon, J., 2006, PTB news - Small world: micro-artifacts, Physikalisch-Technische Bundesanstalt Braunschweig, 6/2, 2.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

4.5 Optimization of cutting parameters using robust design for minimizing energy consumption in turning of AISI 1018 steel with constant material removal rate

C. Camposeco-Negrete [1]

[1] Instituto Tecnológico y de Estudios Superiores de Monterrey Campus Estado de México, México

Abstract
The strategies to reduce energy consumption are obtaining emphasis due to the constant increase in electricity prices, and concern of manufacturing companies and clients about the environmental impact that results from activities related to the production of goods. CNC machine tools, including those that perform turning operations, contribute significantly to the energy consumption in the manufacturing sector.
The present work outlines an experimental study to optimize cutting parameters during turning of AISI 1018 steel under roughing conditions and constant material removal rate, in order to get the minimum energy consumption of the machine tool. Robust design is employed to analyze the effects of depth of cut, feed rate and cutting speed on the response variable.
Keywords:
Energy Consumption Reduction, Robust Design, Turning.

1 INTRODUCTION

The manufacturing of goods has an essential role in the global economy as it provides jobs and economic strength. The manufacturing sector consumes both renewable and non-renewable materials, as well as significant amounts of energy.
Therefore, the objective is to minimize energy consumption in all areas.

The energy consumed in the manufacturing sector is used in production processes which mainly emerge from production equipments. Machine tool is one of the typical production equipments widely used in the industry [1]. In machining processes, saving money and improving sustainability performance can be achieved by reducing energy consumption because energy is an essential resource for production [2].

Improving energy efficiency of manufacturing processes requires knowledge about the energy consumption as a function of the machine tool and cutting process itself. Energy consumption of the machine tool was found to be dependent on the average power demand and the processing time dictated by the cutting parameters [3].

Several works have been previously done so as to optimize machining process taking into account cutting parameters and employing the Taguchi method as a tool for optimization. The aim of the work reported by Bhattacharya et al. [4] was to investigate the effects of cutting parameters on surface roughness and power consumption by employing Taguchi techniques during high speed machining of AISI 1045 steel.

Fratila and Caizar [5] employed the Taguchi techniques to optimize the cutting parameters in order to achieve the best surface roughness and the minimum cutting power in face milling when machining $AlMg_3$. Asiltürk and Neseli [6] minimized the surface roughness in turning of AISI 304 austenitic stainless steel using the Response Surface Methodology (RSM). Hanafi et al. [7] optimized cutting parameters in machining of PEEK-CF30 using TiN tools under dry conditions, to achieve minimum power consumption and the best surface quality. Taguchi optimization and grey relational theory were used in the optimization process.

The work of Newman et al. [8], aimed to investigate if interchangeable machining processes during milling of a block of aluminum alloy 6042 necessarily consume the same amount of power. Four identical slots were machined out with the same tool and spindle speed. The depth of cut and feed were varied to maintain the same cutting time and Material Removal Rate (M.R.R.) for the slots. This study concluded that the power consumption may differ considerably. However, the spindle speed remained constant, so the influence exerted by this cutting parameter in the power consumption cannot be studied.

Diaz et al. [3] studied the energy consumption of the machine during milling of AISI 1018, considering the Material Removal Rate (M.R.R.) as a variable. Nevertheless, the energy consumption of the machine tool when cutting parameters are varied, maintaining the M.R.R. constant, has been not considered.

The works mentioned above show that efforts have been made towards optimization of cutting parameters to minimize power consumption or surface roughness in the machining of steel and aluminum. Most of the investigations focused on turning and employed Taguchi techniques to optimize cutting velocity, feed rate and depth of cut. None of the studies employed the concept of Robust Design to optimize the machining process. Also, the material removal rate was not considered as a constant value so the values of cutting parameters could be varied to find out which level of each parameter reduced the energy consumption of the machine during turning.

Designing high-quality products and processes at low cost is an economic and technological challenge to the engineer. A systematic and efficient way to meet this challenge is the method called Robust Design, introduced by Genichi Taguchi. Its fundamental principle is to improve the quality of

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

a product by minimizing the effect of the causes of variation (called noises) without eliminating them. Signal-to-noise ratio is employed to measure quality and minimize variation around a target value [9].

This paper presents a work done using the Robust Design method for optimizing a roughing turning process with constant M.R.R.. The objective of the experiment was to optimize cutting parameters so as to get the lowest value of energy consumed by the machine during all the machining process, not only in material removal. Two sources of noise were considered: the presence or absence of cutting fluid and the machine tool used to perform the turning operation.

2 ROBUST DESIGN

Robust design is an engineering methodology whose objective is to create high-quality, cost-effective products that perform well during its useful life independently of how and under which circumstances are used. These external circumstances that are outside the control of the design engineering are called noises.

Robust design increases the quality of products minimizing the effect of noise on the performance of the product. In robust design, there are two steps in the optimization process: the first is to maximize the S/N ratio to decrease variability and the second is to adjust the mean to the target value. Quality engineering says that a function should be adjusted to a target value only after reducing variability. Quality engineering is robust design based on the following three procedures: orthogonal array, S/N ratio and loss function [10].

In Taguchi's methodology, the main role of an orthogonal array is to permit engineers to evaluate a product design with respect to robustness. The original Taguchi methodology revolved around the use of a design for the control variables and another design for the noise variables. Then these two designs were crossed; that is, every treatment combination in the design for the control variables was run in combination with every treatment combination in the noise variable design. This type of experiment was called a crossed array design [10]. The design for the control factors is called the inner array design. The design for the noise factors is called the outer array design.

The S/N ratio is a function that can be classified into three categories: nominal is the best characteristic, smaller the better characteristic and larger the better characteristic. For each of these categories, the optimal level of a process parameter is the level which results in the highest value of S/N ratio transformation. When a critical quality characteristic deviates from the target value, it causes a loss. An S/N ratio combines a performance characteristic with its sensitivity to noise factors to measure the quality of a design.

3 TURNING PROCESS: EXPERIMENTAL PROCEDURE

3.1 Selection of process parameters

Turning experiments were performed on 150 mm length AISI 1018 steel cylindrical billets (L/D = 4); cutting length was equal to 50 mm. The experimental investigation was carried out on a HAAS SL10 lathe and on a GILDEMEISTER CTX410 lathe. The cutting tool used was a carbide insert, manufactured by Sandvik (DCMT 11 T3 04 PM). Cutting conditions were absence or presence of conventional flood lubrication.

3.2 Classification of parameters: P diagram

A block diagram representation of the turning process is shown in Figure 1. The response of the process is denoted by *y*. The factors that influence the response are classified into the following classes:

1. Control factors.
2. Noise factors. These factors cause the response *y* to deviate from the target specified.

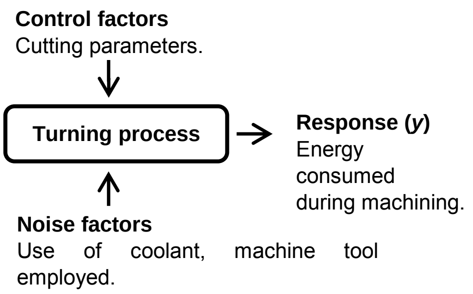


Figure 1. P diagram of the turning process.

The control factors are depth of cut [mm], feed rate [mm/rev] and cutting velocity [m/min]. Noise factors are the presence of conventional flood lubrication or its absence (dry machining), and the type of CNC machine tool employed for performing the process.

3.3 Experimental design

The inner array design selected is composed of nine experiments, with three factors: cutting velocity [m/min] (Factor "A"), feed rate [mm/rev] (Factor "B") and depth of cut [mm] (Factor "C"). In order to maintain a constant M.R.R., the values of the cutting parameters shown in Table 1 were calculated in order to obtain a M.R.R. of 1333.33 mm^3/s. These values are within the operating window recommended by the tool supplier, and they were associated with a level, where "1" is the lowest level and "3" is the highest.

The outer array design has two factors (called Factor K and Factor L) of two levels each one. Level 1 of factor K is the presence of cooling fluid and level 2 is the absence of that fluid. Level 1 of factor L is the machining operation performed in the HAAS SL10 lathe, and level 2 is the same operation performed in the GILDEMEISTER CTX410 lathe.

The experimental design is shown in Table 2, for three experimental trials.

Table 1. Values and levels of cutting parameters.

Exp. no	Factor Values			Factor Levels		
	A	B	C	A	B	C
1	350	0.10	2.29	1	1	3
2	350	0.15	1.52	1	2	2
3	350	0.20	1.14	1	3	1
4	375	0.10	2.13	2	1	3
5	375	0.15	1.42	2	2	2
6	375	0.20	1.07	2	3	1

7	400	0.10	2.00	3	1	3
8	400	0.15	1.33	3	2	2
9	400	0.20	1.00	3	3	1

Table 2. Crossed array design.

Outer array		L	1	1	2	2	1	1	2	2	1	1	2	2
		K	1	2	1	2	1	2	1	2	1	2	1	2
Inner array			*y* (Trial 1)				*y* (Trial 2)				*y* (Trial 3)			
A	B	C												
1	1	3												
1	2	2												
1	3	1												
2	1	3												
2	2	2												
2	3	1												
3	1	3												
3	2	2												
3	3	1												

3.4 Power measurement system

Power required from the grid during the turning process was measured through a LabVIEW interface, and it was recorded each 0.1 s from the main switch of each one of the lathes. In order to obtain the value of the energy consumed by the machine, average power was computed and then multiplied by the cycle time.

4 RESULTS

The results obtained regarding average energy consumption in turning process are shown in Table 3.

Table 3. Energy consumed by the machine tool in turning process

Outer array		L	1	1	2	2	1	1	2	2
		K	1	2	1	2	1	2	1	2
Inner array			*y* avg [kJ]				Cycle time [s]			
A	B	C								
1	1	3	74.2	133.1	71.5	121.0	9.6			
1	2	2	54.3	97.2	51.6	88.8	6.5			
1	3	1	43.6	80.8	42.9	73.1	4.9			
2	1	3	71.1	135.7	69.0	124.0	9.0			
2	2	2	52.5	100.2	51.7	91.2	6.1			
2	3	1	43.0	82.7	42.0	76.3	4.6			
3	1	3	69.5	141.8	67.9	130.6	8.5			
3	2	2	52.2	105.9	50.4	97.3	5.7			
3	3	1	42.1	86.7	41.1	81.4	4.3			

4.1 Main effects plot

The main effects analysis is used to study the trend of the effects of each of the factors. Main effects plot for the three factors considered in the inner array (cutting velocity, feed rate and depth of cut) versus energy consumed is shown in Figure 2.

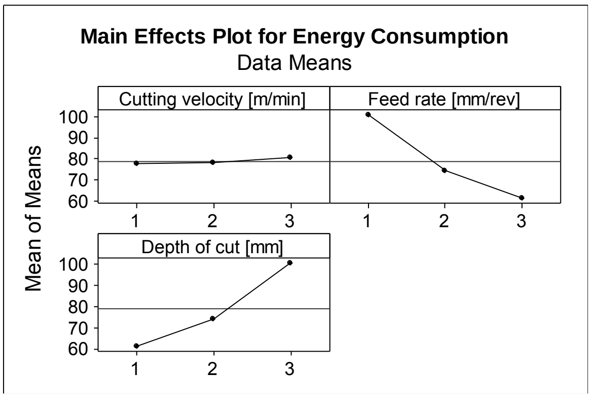


Figure 2. Main effects plot for energy consumed per machining cycle.

4.2 S/N ratio plot

The S/N ratio measures performance characteristics of the process and helps to reduce its variance and prevent its deviation from the target value. The S/N ratio is calculated based on the smaller the better characteristic because the aim of the experiments was to minimize energy consumption in the machining process. S/N ratio was calculated as

$$S/N = 10log[(1/n)*(\Sigma y^2)] \quad (1)$$

where y is the observed data and n is the number of observation. S/N ratio plot for the three factors is shown in Figure 3.

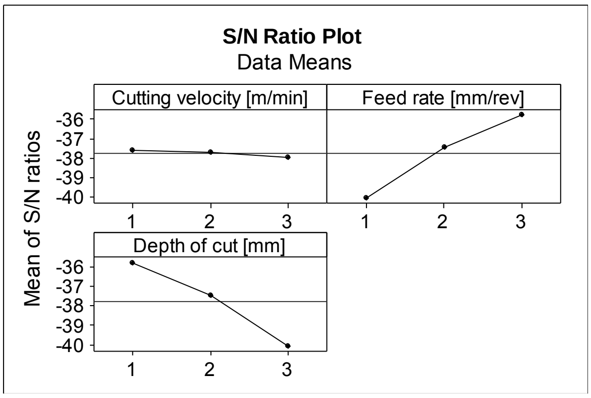


Figure 3. S/N ratio plot for energy consumed per machining cycle.

5 DATA ANALYSIS AND DISCUSSION

According to the main effects plot (Figure 2), the energy consumed per machining process decreases with levels A1, B3, C1. The slope of the graphs in the Figure 2 shows that feed rate and depth of cut are the parameters that influence the response variable the most.

Referring to S/N ratio plot (Figure 3), the levels of each of the three factors that should be used in order to reduce process variance are the same as the ones indicated by the main effects plot. These levels decrease the value of the energy consumed and ensure the process will stay in its target value.

Energy consumed per machining process is lower when the values of depth of cut and cutting velocity are diminished and feed rate is increased. A higher value of feed rate reduces the time required to machine the material and, as a consequence, less energy is needed to perform the operation.

Minimum cutting velocity is necessary for obtaining the minimum energy consumed in the machining operation. A higher value of cutting velocity implies more energy to move the spindle from rest to the indicated value of RPMs.

Sandvik Corokey [11] points out that cutting velocity is the parameter that reduces tool life the most. Furthermore, this parameter at higher values increases energy consumption. Cutting velocity must be kept at its minimum value (350 m/min), to optimize energy consumption and to avoid excessive tool wear.

Minimum depth of cut is necessary for optimizing energy consumption during machining. An increment of this factor implies a rise of the value of the force needed to remove the material, so the system is forced to spend energy. As depth of cut increases heat generated at the tool workpiece interface also increases.

According to Dahmus and Gutowski [12], the energy consumed by the machine outside of chip formation is significant because less than 15% of the total energy consumed by an automatic machine tool is related to the material removal. Therefore, it is important to go beyond the tool-chip interface in order to understand the energy consumption of the machine.

For the nine experiments presented in Table 1, although the M.R.R. is the same for all of them, the energy consumption varies according to the cutting parameters' selection. This is due to the fact that each experiment has a different cycle time. If the cycle time of the experiment is greater, the energy consumption increases, compared to an experiment with less cycle time. In general, the lower the cycle time, the lower the total energy consumed by the machine tool.

6 CONCLUSIONS

In this study, Robust Design was used to identify the main effects of three factors (cutting parameters) on the energy consumed during turning of AISI 1018 steel with constant material removal rate.

As shown in Table 2, experiments with the same M.R.R. do not have equal values of energy consumed, because the energy consumption is related to the values of the cutting parameters chosen. Therefore, different combinations of values of cutting parameters can have identical amounts of material removed but the energy consumption of each one of these combinations will not be the same.

This study thus concluded that the third level of feed rate (0.2mm/rev), first level of depth of cut (1.14mm) and first level of cutting velocity (350 m/min) lead to minimum energy consumption and less variation of the process from the target value in the case of machining AISI 1018 steel with constant material removal rate.

7 ACKNOWLEDGMENTS

The author would like to thank the Consejo Nacional de Ciencia y Tecnología (CONACyT) and the ITESM Campus Estado de México for providing financial resources.

8 REFERENCES

[1] Cao, H., Li, H., Cheng, H., Luo, Y., Yin, R., hen, Y., 2012. A carbon efficiency approach for life-cycle carbon emission characteristics of machine tools. Journal of Cleaner Production 37, 19 – 28.

[2] Pusavec, F., Krajnik, P., Kopac, J., 2010. Transitioning to sustainable production - Part I: application on machining technologies. Journal of Cleaner Production 18, 174 – 184.

[3] Diaz, N., Redelsheimer, E., Dornfeld, D., 2011. Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use. Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 263 - 267.

[4] Bhattacharya, A., Das, S., Majumber, P., Batish, A., 2009. Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. Production Engineering: Research & Development 3, 31 – 40.

[5] Fratila, D., Caizar, C., 2011. Application of Taguchi method to selection of optimal lubrication and cutting conditions in face milling of AlMg3. Journal of Cleaner Production 19, 640 – 645.

[6] Asiltürk, I., Neseli, S., 2011. Multi response optimisation of CNC turning parameters via Taguchi method-based response surface analysis. Measurement 45, 785 – 794.

[7] Hanafi, I., Khamlichi, A., Mata Cabrera, F., Almansa, E., Jabbouri, A., 2012. Optimization of cutting conditions for sustainable machining of PEEK-CF30 using TiN tools. Journal of Cleaner Production. 33, 1 – 9.

[8] Newman, S.T., Nassehi, A., Imani-Asrai, R., Dhokia, V., 2012. Energy efficient process planning for CNC machining. CIRP Journal of Manufacturing Science and Technology. 5, 127 – 136.

[9] Montgomery, D.C., 2009. Design and Analysis of Experiments. John Wiley & Sons, Inc., New York.

[10] Taguchi, G., Chowdhury, S., Wu, Y., 2005. Taguchi's Quality Engineering Handbook. John Wiley & Sons, Inc., Hoboken, New Jersey, pp.56-125.

[11] SANDVIK Coromant, 2010. Corokey 2010. <www.sandvik.com> (accessed on 18.12.12).

[12] Dahmus, J., Gutowski, T., 2004. An Environmental Analysis of Machining. Proceedings of ASME International Mechanical Engineering Congress and R&D Exposition, pp. 13 - 19.

GCSM 11th Global Conference on Sustainable Manufacturing
2013 23rd - 25th September Berlin - Germany

4.6 Energy consideration in machining operations - towards explanatory models for optimisation results

O.O.Owodunni, T. Zhang, J. Gao

Centre for Innovative Product Development and Manufacturing, School of Engineering, University of Greenwich, Chatham Maritime, Kent, ME4 4TB, UK

Abstract

This paper reports the application of a systematic research methodology for uncovering the reasons behind results obtained when energy is considered in machining optimisation. A direct search optimisation method was used as a numerical experimentation rig to investigate the reasoning behind the results obtained in applying Taguchi methods and Genetic algorithm (GA). Representative data was extracted from validated machining science equations and studied using graphical multivariate data analysis. The results showed that over 80% of reduction in energy consumption could be achieved over the recommendations from machining handbooks. It was shown that energy was non-conflicting with the cost and time, but conflicting with quality factors such as surface roughness and technical factors such as power requirement and cutting force. These characteristics of the solutions can provide an explanative motif required for practitioners to trust and use the optimisation results.

Keywords:

Direct search method, energy minimisation, machining optimisation, sustainable machining operation

1 INTRODUCTION

Minimising the energy consumption for the machining process can lead to benefits for the environment as well as contribute to economic and social well being of the society. Duflou et al. [1] concluded that optimising manufacturing process is one of the strategies to reduce energy demand and resource consumption. The specific methods for optimising manufacturing process include reducing auxiliary energy consumption, reducing idle production time, optimising process parameters and energy-efficient process planning. Previous research [2] of the authors looked at the improvement of energy efficiency for end milling operation. An energy prediction model and energy-efficient profiling toolpath strategy have been proposed. The aim of this paper is to continue investigating energy minimisation methods by considering optimisation of process parameters to further improve the energy usage for machining operation. The characteristics of machining operation when energy is considered as a significant factor will be investigated. A direct search optimisation method will be used to uncover the reasoning of the optimal results which are obtained when using Taguchi method and genetic algorithm.

1.1 Problems for Machining Optimisation

The observation from literatures and practice is that currently, too many optimisation methods (such as Genetic Algorithm (GA), Simulate Annealing (SA), Particle Swam Optimisation (PSO) and tribe/ant-colony) have been proposed. The optimisation methods are more like "black box" tools. The consequence of this problem is that in practice, the practitioners do not trust the optimal results because they cannot understand how the results are obtained from the optimisation methods.

1.2 Research Question and Research Design

The following research questions are going to be answered in this paper:

How the nature of the energy-minimising machining optimisation problem be explained?

How the reasoning process of the algorithms for solving the energy-minimising machining problem be explained?

To address the challenge posed by these research questions, this paper presents in section 3 an exploration of techniques for explaining the characteristics of the optimisation problem and in section 4 the reasoning behind the algorithms for solving the optimisation problem. A review of related research is presented in section 1.3 to introduce the development of machining optimisation and identify the gaps of knowledge.

1.3 Related Research in Machining Optimisation

The research of improving machining performance by selecting optimal process parameters have been conducted for over 100 years since Taylor published his tool life equations in the early 1900s [3]. Early researchers (1950s to 1970s) proposed optimal suggestion based on analysis of machining variables. The optimisation process usually followed procedures of (1) data collection through conducting physical experiments, (2) mathematically modelling (3) analysing the mathematical equation, and (4) proposing optimal solutions. Following this type of approach, Brewer and Rueda applied a monograph technique to optimise tool life with the consideration of a group of independent variables for turning variety of materials. The results showed that for non-ferrous materials, the best cutting conditions are regarded as the high material removal rate which the machine will permit. For difficult-to-machine material the range of feasible parameters is much narrower than non-ferrous material [4]. Crookall proposed a concept of performance-envelope to represent the permissible and desirable operation regions of machining based on the characteristics of machining cost and time with the constraints of machining tool capability (power), cutting tool failure, and surface roughness [5].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

On the basis of early research, conventional optimisation methods started to be applied in machining optimisation during 1980s to 1990s. Researchers from University of Manchester used a grid search method to solve machining optimisation [6]. Enparatza [7] developed a tool selection module for end milling operation and conducted an optimisation procedure of cutting conditions by considering economic criteria. The result reported that the machining cost can be minimised by selecting optimal cutting speed. The optimisation procedure also showed how constraints (tool life, cutting force, machining power and tool deflection) affect the search space. By comparing different algorithms, Tolouei-Rad and Bidhend selected feasible direction method to optimise general milling operation based on economic criteria. They reported that the optimisation of end milling is a non-convex, non-linear, multi-variable and multi-constrained problem. A case study of machining a multiple-feature component showed that up to 350% improvement in profit rate can be achieved over the recommendation from machining handbook [8].

Taguchi method was introduced to improve product and process design as a fractional factor design method which can significantly reduce time and resource needed compared to conventional Design of Experiment (DOE) methods. In addition, because it can be easily implemented and has a good applicability, the Taguchi method has been widely used in many machining optimisation research to determine important process parameters based on economic criteria (e.g. cost, productivity) and surface roughness [9].

With the rapid development of computer technology in early 21st century, new optimisation methods which are generally known as Evolution Computing or Meta-Heuristic search algorithms have become popular in machining optimisation. Heuristic algorithms are widely used to solve parameter optimisation problems, especially when the search space is very large and complex. Khan et al. [10] claimed non-conventional algorithms such as Genetic Algorithm (GA) and Simulated Annealing (SA) are more suitable than traditional methods for machining optimisation due to its non-linear and non-convex solution space. Baskar et al. [11] compared the performance of four non-conventional methods: Ant Colony Algorithm, GA, PSO and Tabu Search. They applied theses methods to determine the optimal process parameters when time, cost and profit rate are the objective functions. The results showed that PSO has better performance than the other algorithms. It was reported that 440% and 54% of improvement in profit rate was achieved compared to handbook recommendation and optimal result by using feasible direction method. However, comparison of the results obtained from GA and PSO showed that the optimal results for these algorithms do not differ by more than 4%.

Until recently, energy was indirectly considered in machining optimisation through including power as a constraint in the optimisation problem. Energy was first considered as a primary objective by Fillippi and Ippolito in 1980 [12], but it was not until the mid of the 1990s that Sheng et al. [13] formulated an environmentally-conscious multi-objective model which considered energy consumption as an important component. It also provided a possible way to carry out an optimisation procedure from environmental perspective. Based on consideration of energy minimisation, Rajemi and Mativenga [14] conducted research on optimising cutting parameters for dry turning operations. A prediction model was developed in terms of feed rate, cutting velocity and tool life to calculate energy consumed. Further research by Mativenga and Rajemi [15] showed that by optimising tool life through direct search method, up to 64% energy can be reduced compared to that obtainable by using cutting parameters recommended by tool suppliers. In addition, the optimal value of cost can be achieved at the same time with optimal energy consumption. Mori et al [16] conducted a series of experiments based on Taguchi method. The results showed that cutting performance can be improved by adjusting cutting speed, feed rate, depth and width of cut. Up to 66% power consumption for milling operation can be reduced by selecting high level of cutting conditions within a value range which does not compromise tool life and surface finish. The machining time can also be shortened with significant increase in material removal rate.

1.4 Summary of Gaps from Literature

The environmental challenge provides a new opportunity to apply the results of decades of optimisation and process planning research. However, as identified by Roy et al [18], most of academic optimisation results have not been used by industry because practitioners mostly prefer to select optimal parameters based on expert experience. The reasoning behind practices on optimisation [11-16] is not clear and needs to be transparent by addressing the following requirements:

- The optimisation procedure must be based on comprehensive understanding of the problem.
- The primary objective (energy) must be related to the conventional objectives such as cost, time and quality which the practitioners are familiar with and interested in.
- The optimisation method adopted must be concise and explicit which is relevant to practitioners' knowledge or obvious general principle.
- The optimisation results must be easily visualised.

2 NATURE OF MACHINING OPTIMISATION

2.1 Nature of Search Space

Search space can be explained as a set of all the possible solutions. Each point in the search space represents a combination of process parameters. The size of the search space increases exponentially with the increase of number and levels of variables. Thus, for 3 levels of 4 variables the total number of size of the search space is 3^4. The increasing the number of levels by 1 will expand the size to 4^4 which increases search space by over 300%.The unconstrained search space of machining optimisation is a multi-dimensional space located in the positive interval of the coordinate space.

2.2 Nature of Variables

The variables involved in end milling operation have already been identified and classified into independent and dependent variables by several researchers [2, 4, 7, 8, 11, 16]. These variables are listed below.

Independent variables: Depth of cut ap (mm), Width of cut ae (mm), Feed rate fz (mm/tooth), Spindle speed n (rev/min), Diameter of tool d (mm), Number of flutes z.

Dependent variables: Energy E (kJ), Cost C, Time T (min), Material Removal Rate MRR, Tool Life TL (min), Cutting Force F (N), Power P (W), Surface Finishing Ra, Cutting Speed Vc, Feed Rate f (mm/min)

2.3 Nature of Objectives and Constraints

Previous machining research contributions [4, 7, 8, 10, 11] have used as objectives cost, time, surface roughness and tool life, and as constraints the following variables:

- The surface roughness should be satisfied with the quality requirement (rough machining or finishing)
- The cutting force should at least make sure the machining operation can take place but not break the cutting tool.
- The power required for machining should not be over the limitation of the machine tool
- Physical constraints of independent variables determined by the capability of machine tools (design power) and cutting tools geometries (diameter of the tool).

In this paper, energy is added to these dependent variables and can be considered either as the objective function or constraint. For the purpose of investigating the problem any of the other factors can also be either an objective or constraint or both.

3 CHARATERISATION OF ENERGY CONSUMPTION

3.1 Design of Numerical Experiment

Numerical experiments carried out in this paper are mainly based on predictive models obtained from previous experiments conducted by the authors [2] when milling Aluminium 7050 on a HAAS TM-1CE 3-axis vertical milling machine. Equations for variables such as tool life and surface roughness are obtained from the contributions of other researchers [2, 8, 11]. The design of numerical experiment is shown in Table 1. Table 2 lists the mathematical expressions of the dependent variables for the numerical experiments. Four process parameters are considered as independent variables which are: depth of cut, width of cut, spindle speed and feed rate per tooth.

Table 1: DOE for numerical experiment

Process Parameter	Value Range
Depth of cut ap (mm)	1-5 mm
Width of cut ae (mm)	1-10 mm
Spindle Speed n (rpm)	500-4000 rpm
Feed rate fz (mm/z)	0.01-0.1 mm/tooth
Diameter of tool (mm)	10 mm
Number of flutes	3
Cutting Tool: carbide flat end mill	
Workpiece material: Aluminium 7050	

3.2 Characteristics of Machining Operation with Energy Consideration

Since the studies of other factors have been considered by other researchers [4-7], this paper will only focus on the factors in relation to energy consumption. Numerical experiments were carried out based on the prediction models in Table 2 in the range of process parameters in Table 1. The effects of four independent variables on energy consumption are shown as in Figure 1. The results show that the energy consumption for machining specific volume material monotonously decreases with the increase in depth of cut, width of cut, feed rate and spindle speed. It means choosing higher machining parameters is more energy efficient than using lower parameters.

Table 2: Mathematical expressions of dependent variables

Feed Rate: $f = n \cdot z \cdot f_z$
Mater Removal Rate: $MRR = a_p \cdot a_e \cdot f$
Cutting Speed: $v_c = n \cdot \pi \cdot d$
Cutting Force: $F_t = 2K_t \cdot MRR / (n \cdot z \cdot d)$
Force Coefficient: $K_t = c_{k0} \cdot a_p^{c_{k1}} \cdot a_e^{c_{k2}} \cdot d^{c_{k3}} \cdot z^{c_{k4}} \cdot f_z^{c_{k5}} \cdot n^{c_{k6}}$ Where c_{k0} to c_{k1} are coefficients for Kt
Total Power: $P_{total} = P_{machining} + P_{auxiliary} = \frac{F_t \cdot v_c}{60} + P_{constant} + P_{variable}$ Where the other components are power consumptions for machining, auxiliary functions (constant and variable)
Tool Life: $TL = \frac{c_{tl}}{v_c^m \cdot f^p \cdot a_p^q}$ Where m, p, q are tool life coefficients
Total Time: $t_{total} = t_{machining} + t_{setup} + t_{tc} = \frac{V_m}{MRR} \cdot \left(1 + \frac{t_{change}}{TL}\right) + t_{setup}$ Where the other components are time consumptions for machining, setup, tool change(tool change/time)
Total Energy: $E_{total} = E_{machining} + E_{auxiliary} + E_{setup} + E_{tc} = t_{total} \cdot P_{total} + (t_{setup} + t_{tc}) P_{constant}$ Where the other components are energy consumptions for machining, auxiliary function, setup, tool change
Total Cost: $C_{total} = C_{Labour} + C_{Energy} + C_{tool}$
Ra: $R_a = c_{r0} \cdot a_p^{c_{r1}} \cdot a_e^{c_{r2}} \cdot d^{c_{r3}} \cdot z^{c_{r4}} \cdot f_z^{c_{r5}} \cdot n^{c_{r6}}$ Where c_{r0} to c_{r1} are surface roughness coefficients

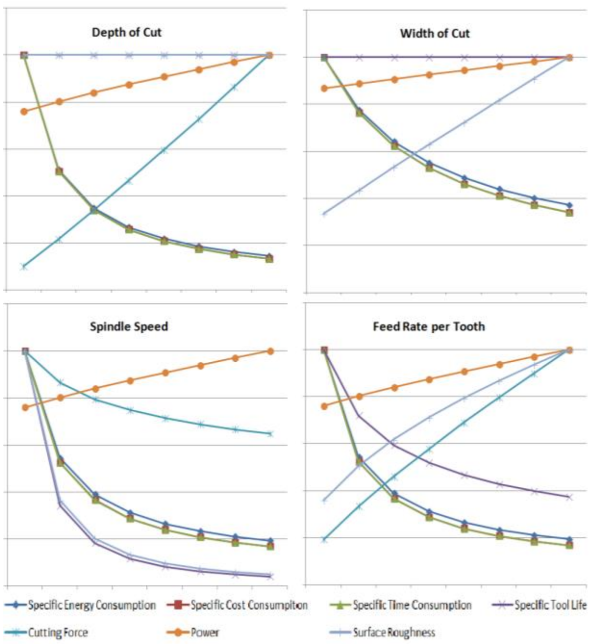


Figure 1: Characteristics of Machining Operation

Another observation from the energy plots of figure 1 is that the improvement trend of energy is less pronounced with the increase of process parameters. One reason is that the increase of process parameters can only reduce the energy consumed by machining operation, but cannot reduce the constant energy consumption such as the energy consumed for setting up the machine tool. The comparison between energy consumption and other criteria shows that energy is non-conflicting with the cost and time for all four independent variables. However, energy consumption is conflicting with cutting force in depth of cut and width of cut, surface roughness in width of cut and feed rate per tooth, tool life in spindle speed and feed rate per tooth, and power in all four independent variables.

4 INVESTIGATION OF OPTIMISATION METHODS

4.1 Development of Experimentation Rig based on Direct Search Method

The principle of direct search method is similar to full factorial DOE. Grids will be created based on numbers and levels of independent variables which represent all the possible solutions which will be used to create the experimentation rig. Table 3 shows a 3 levels DOE plan. 81 grids points will be created.

Table 3: 3 Levels Design of Experiment

Process Parameter	Level 1	Level 2	Level 3
Depth of cut a_p (mm)	1	3	5
Width of cut a_e (mm)	5	7.5	10
Spindle Speed n (rpm)	500	2250	4000
Feed rate f_z (mm/z)	0.01	0.055	0.1

The experimentation rig can be graphically displayed in Figure 2. The label of horizontal axis was removed since it only represents the numerical order of samples (1 to 81) which does not have any physical meaning. The original data after initial multivariate data analysis shows the energy consumption is changing with some pattern which can be displayed as dash squared areas to represent the original searching space of 3 level 4 variables full factor design. Each small dash square area contains 9 grid points which correspond to every 9 points on the original energy plot. The blue arrows shows the increasing direction of the 4 process parameters (e.g. No. 5 block contains the data when ap=3, n=2250, ae=5-10 and fz=0.01-0.1). The highlighted green area shows the data after being sorted with the increase of material removal rate per tooth (MRRz). The red curve shows the samples after being organised with continuing decrease of specific energy consumption.

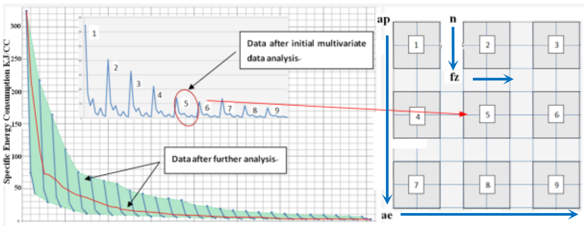


Figure 2: Experimentation rig of specific energy consumption.

4.2 Explanation of Taguchi Method

Taguchi method is an experiment-based optimisation method which uses a concept of “signal and noise (S/N)” ratio to evaluate the impact of the variables by considering the average value and standard deviation. For the objective of minimising energy consumption, the smaller the better equation will be chosen to calculate S/N ratio:

$$S/N_s = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} Y^2\right) \quad (1)$$

Table 4 shows an L9 DOE plan according to Taguchi orthogonal experimental design. 9 out of 81 samples were selected to carry out the analysis.

Table 4: Experimental results of Taguchi method

Number	ap	ae	n	fz	SEC
1	1	5	500	0.01	323.945
2	1	7.5	2250	0.055	11.207
3	1	10	4000	0.1	4.274
4	3	5	2250	0.1	4.856
5	3	7.5	4000	0.01	11.855
6	3	10	500	0.055	12.761
7	5	5	4000	0.055	3.954
8	5	7.5	500	0.1	7.165
9	5	10	2250	0.01	10.265

The graphical explanation is shown in Figure 3. The black dots on the grids represent the selected samples in Table 5. From the observation of these dots, it can be found that each dot is located on a unique position of each dash area (e.g. upper left, middle, lower right). It means each level of parameters only interacts once, hence avoids overlapping consideration. The basic principle of Taguchi method is to use S/N ratio to analyse the fractional effect of the variables to identify which level of which parameter has greater influence on the machining performance. The optimal results then will be determined by adjusting cutting conditions based on the fractional effects. Figure 3 shows the analysing process of depth and width of cut. It can be found that the analysis follows the increase of the variables. It shows that the nature of the Taguchi method is actually the same as gradient search or feasible direction method.

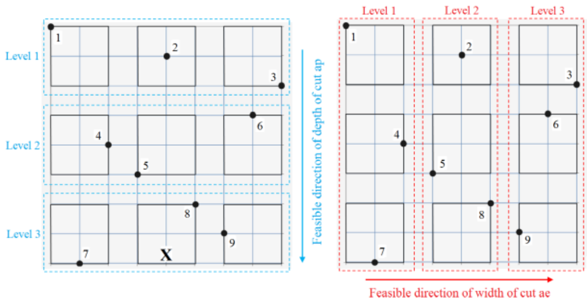


Figure 3: Display of Taguchi samples

In using the Taguchi method for optimisation of process parameters, the first observation obtained from the S/N plot of figure 4 is that optimal values of energy is obtained at the highest levels for all the 4 parameters. The second observation is that for improving the energy consumption it is more efficient to increase the process parameters in the order feed rate, depth of cut, spindle speed and lastly width of cut. While these observations can be obtained by other conventional data analysis methods as the characterisation of figure 1, the Taguchi method makes this information much clearer. However as pointed out in the literature, this usage of the Taguchi method for optimisation is only a first level approximation as it could miss the real optimal value. For example in figure 3, if the optimum is at point X, the optimum indicated by applying the Taguchi method as describe above will not be the real optimum. For cases like this the use of Taguchi method will require an iterative approach, in which the experiment is repeated in the vicinity of optimum obtained in a previous step. When the results obtained in this iterative application the Taguchi method are considered, the method will be it appears similar to the feasible direction or steepest ascent/decent optimisation methods.

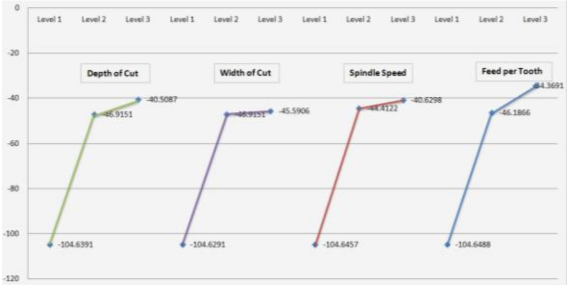


Figure 4: S/N ratios for process parameters.

4.3 Explanation of Genetic Algorithm (GA)

Table 5: Concept comparison between GA and machining

GA	Machining
Population	Feasible machining plans
Individual	A machining plan
Chromosome	Combination of parameters
Gene	Parameter
Fitness	Optimum value
Selection	Record improved results
Reproduction	Change the combination of machining parameters
Crossover	
Mutation	
Evolution	Generate new optimal results

Table 5 shows the explanation of GA in machining terms. Typical GA-based optimisation steps and the explanation in machining optimisation terms are presented below.

1. Random selection of starting points (process parameters). It is difficult to find a completely random selection of starting process parameters in practical machining operation. Even for a novice practitioner who is working on new machining operations (e.g. new material, tool and machine tool) where the best process parameters are not known yet, the selection of the process parameters would be guided by suggestions from machining handbook, tool catalogue or the experience of senior practitioners. A possible explanation of this random selection cannot also be justified by a case of an intelligent machine tool designed to adaptively determine the cutting parameters since database values would usually provide initial values.

2. Generate new individuals by conducting crossover and mutation. The function of crossover is to rapidly explore a search space within the initial data range which is the same as changing the combination of process parameters to achieve the new machining plans. The function of mutation is to provide a small amount of random search which can expand the search space by extending data range. It is the same as replacing a process parameter with a new value (e.g. increase the depth of cut from 1mm to 3mm or vice versa) which leads to a new set. The randomisation explanation of step 1 applies here too.

3. Select and keep the best individual. The function of selection is to compare the machining plans and keep record of the optimal plans for further operation. The best machining plan can be determined by repeating above operations. Figure 5 graphically shows how the optimal result is obtained by using GA for an example. The optimal result can be determined after repeating the algorithm 4 times. The green dash arrow shows the overall search path of implementing GA which is similar to feasible direction optimisation method. However, the results obtained from crossover and mutation operations are not always positive. In this case, the actual optimisation path (grey arrow) is similar to hill climbing method which can determine the local optimal value within the data range. However, the repeated mutation operation can help jump out of previous local search space and eventually find the real optimal specific energy consumption.

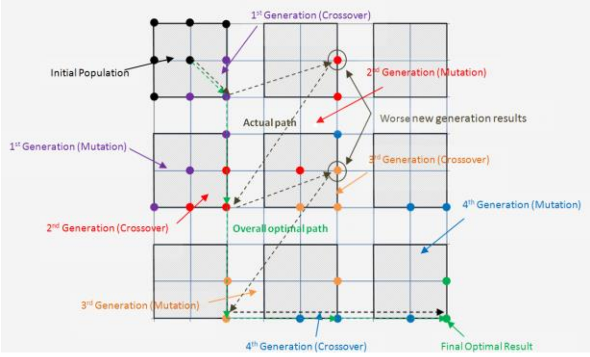


Figure 5: Determination of optimal results by using GA.

In addition, the sample size and location of the initial population also affect the performance especially the speed of optimisation process in terms of interaction numbers, number of generations and computing time. However, they will not affect the value of optimal results.

5 OPTIMISATION PROCEDURE

According to characteristics of machining operation, the optimisation procedure was conducted by using direct search algorithm. The optimal result is located on the boundary of the search space. Figure 6 shows 1 of the 9 solution landscapes for the 3 level, 4 variable energy-minimisation machining problem. In the figure, Specific Energy Consumption, SEC reduces with the increase in feed rate and spindle speed.

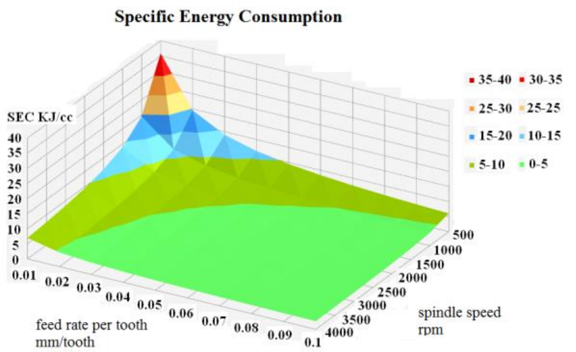


Figure 6: 3D Contour plot of SEC

Figure 7 shows search space with the constraints by the cutting force and surface roughness factor displayed. The green area represents the feasible region of search space when cutting force is no more than 400N and surface roughness is smaller than 0.05mm. So the optimal cutting condition based on energy consideration is the optimal points highlighted in the figure. The optimal result in Table 6 shows that over 80% of improvements in energy, cost and time can be achieved compared to machining handbook recommendation [18].

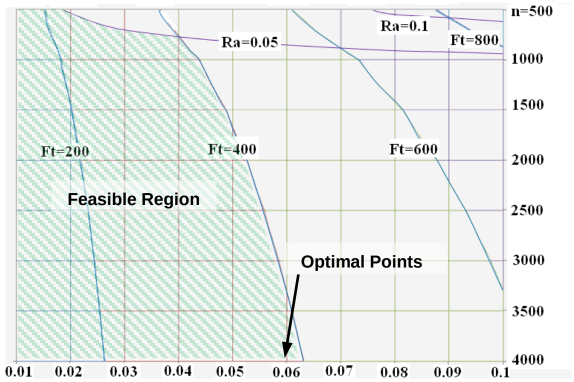


Figure 7: Constrained Optimal Results.

Table 6: Optimal Results Comparison

Variables	Handbook	Optimal	Improvement
ap (mm)	1	5	
ae (mm)	5	10	
n (rpm)	1500	4000	
fz (mm/tooth)	0.067	0.06	
Energy (KJ/cc)	18.612	3.079	83.46%
Cost (£/cc)	0.123	0.016	86.99%
Time(sec/cc)	43.968	5.833	86.73%

6 CONCLUSION

This paper presented a systematic research methodology for uncovering the reasons behind results obtained when energy is considered in machining optimisation. It provided the answers to the research questions in the following aspects:

- Energy consumption monotonously decreases with the increase of process parameters. It is non-conflicting with the cost and time, but conflicting with surface roughness, power requirement, tool life and cutting force.
- Explanation models developed show that Taguchi and GA are similar to feasible direction methods. The transparency from the explanations can help practitioners to trust and implement optimisation results.
- The constrained optimisation result shows that over 80% of improvement of energy, cost and time can be achieved by using optimal process parameters compared to machining handbook recommendation.

7 REFERENCES

[1] Duflou J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012, Towards Energy and Resource Efficient Manufacturing: A Process and Systems Approach, CIPR Annals- Manufacturing Technology, 61:587-609

[2] Zhang, T., Owodunni, O.O., Gao, J., Habtay, Y., 2011, Energy-efficient Toolpath Strategy for End Milling Operation, in: Proceedings of 9th International Conference on Manufacturing Research, Glasgow, UK

[3] Taylor, F.W., 1907, On the Art of Cutting Metals, ASME Journal of Engineering for Industry, 28: 310-350

[4] Brewer, R. C., Rueda, R., 1963, A Simplified Approach to the Optimum Selection of Machining Parameters, Engineers Digest, 24(9): 133–150

[5] Crookall, J.R., 1969, The performance-envelope concept in the economics of machining, International Journal of Machine Tool Design and Research, 9(3): 261-278

[6] Hinduja, S., Petty, D.J., Tester, M., Barrow, G., 1985, Calculation of optimum cutting conditions for turning operations, Proceedings of the Institution of Mechanical Engineers, 199(B2): 81-92

[7] Enparantza, R., 1991, Tool Selection and Cutting Conditions Optimization in Milling, PhD Thesis, University of Manchester

[8] Tolouei-Rad, M. and Bidhendi, M., 1996, On the Optimization of Machining Parameters For Milling Operations, International Journal of Machine Tools and Manufacture, 48: 609-628

[9] Mukherjee, I., Ray, P.K., 2006, A review of optimisation techniques in metal cutting processes, Computers & Industrial Engineering, 50: 15-34

[10] Khan, Z., Prasad, B., and Singh, T., 1997, Machining condition optimisation by genetic algorithms and simulated annealing, Computers Optimisation Research, 24(7): 647-657

[11] Baskar, N., Asokan, P., Saravanan, R., Prabhaharan, G., 2005, Optimisation of Machining Parameters for Milling Operations Using Non-conventional Methods, International Journal of Advanced Manufacturing Technology, 25: 1078-1088

[12] De Fillippi, A., Ippolito, R.,1981, NC machine tools as Electric Energy Users, CIRP Annals, 30: 323-326

[13] Munoz, A.A., Sheng, P., 1995, An analytical approach for determining the environmental impact of machining process, Journal of Materials Processing Technology, 53(3): 736-758

[14] Rajemi, M.F., Mativenga, P.T., and Aramcharoen, A., 2010, Sustainable machining: selection of optimum turning conditions based on minimum energy considerations, Journal of Cleaner Production, 18: 1059-1065

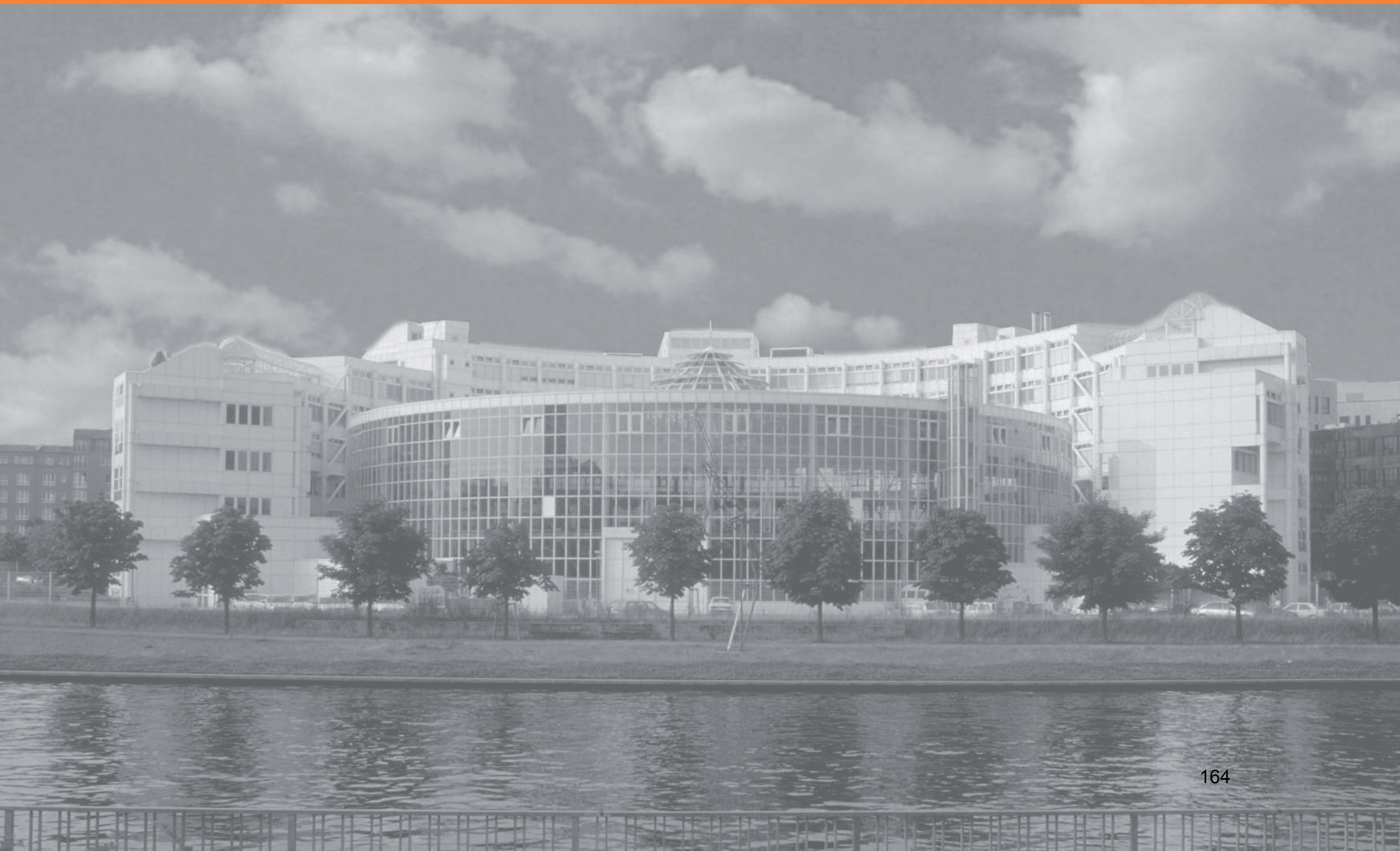
[15] Mativenga, P.T. and Rajemi, M.F., 2011, Calculation of optimum cutting parameters based on minimum energy footprint, CIRP Annals-Manufacturing Technology, 60: 149-152

[16] Mori, M., Fujishima, M., Inamasu, Y., and Oda, Y., 2011, A Study on energy efficiency improvement for machine tools, CIRP Annals- Manufacturing Technology, 60 (1), 145-148

[17] Roy, R., Hinduja, S., Teti, R., 2008, Recent advances in engineering design optimisation: Challenges and future trends, CIRP Annals-Manufacturing Technology, 57: 697-715

[18] WNT2012 Catalogue, 13 Solid Carbide Milling Cutter

Session 5
Knowledge



GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

5.1 Regional investment attractiveness in an unstable and risky environment

Nikolova Liudmila
Ekaterina Plotnikova
Sub – faculty “Finances and monetary circulation” Saint Petersburg state polytechnical university, Russia

Abstract
Investment process effectiveness, which along with investment risk and investment potential defines the investment attractiveness of a region, and, therefore, the investment climate, is also characterized by the growth of regional gross product through investments in physical and human capital. The investment attractiveness of a region is determined by comparison of two parameters reflecting the conditions in which investors’ activities take place: investment potential and investment risk. The amount of risks associated with investment activities is large, while uncertainty of their occurrence compels investors to evaluate the investment potential of a region as uncertain, too. Eliminating uncertainty in investment risk evaluation and increasing investment attractiveness of regions may be possible through application of logical and stochastic methods of evaluation, to the author's mind.

Keywords:
Investment attractiveness, risk factor, geographical region, logical stochastic methods.

1 INTRODUCTION

The current state of development of many Russia's regions speaks of a need for both national and international investment. Attracting investors to the Russian market is a hard task because attempts to assess regional investment activities have been rather rough than accurate. Unified approaches to interpretation and composition of indicators are inexistent. The worst problem here is that there are no unambiguous assessment of investment climate and risks of a region. A region's investment domain is a combination of interrelated businesses that are all involved in the processes of accumulation, placement and efficient use of capital as part of investment activities. This domain of economy is not homogeneous; it is an intricate development whereby each participant of investment process, proceeding from its economic interest, carries out a purposeful investment activity. Channeling investment to this or that region is dictated by its investment attractiveness and by the level of investment risk. These are the two variables that influence the amount of capital invested in the region. To evaluate investment attractiveness of a region we have to look at the relevant investment potential index, whose formation is considered in the paper. Assessment of investment risk is possible, according to the author, by applying logical stochastic mathematical assessment models. This approach will allow a potential investor to take an informed decision with a minimized risk of getting poor investment results.

2 INVESTMENT POTENTIAL OF A REGION

2.1 Building the index of investment potential

Investment process effectiveness, which along with investment risk and investment potential defines the investment attractiveness of a region, and, therefore, the investment climate, is also characterized by the growth of regional gross product through investments in physical and human capital. It should be noted that the growth of gross regional product may be due to a considerable number of factors which, in their turn, depend on the goal that has been defined by existing regional policies and strategy.

Investments in physical and human capital are the two factors that have the greatest impact on the growth of gross regional product. This domain of economy is not homogeneous, it is an intricate process whereby each participant of investment developments, proceeding from its economic interest, carries out a purposeful investment activity playing at times the role of either investor or investment recipient. This is a reason why investment should be viewed as a system, a combination of interrelated businesses, making up a whole, that are interrelated and interacting in the processes of accumulation, placement and efficient use of capital with the aim of its enlarged reproduction. This gives us grounds to recognize that a region's investment activities are a complex system which, on the one hand, is part of a higher level system, and on the other - is itself a combination of elements that are individual sub-systems themselves [2]. Research of the behavior of such a system is needed for a comprehensive assessment of a region's investment climate, the one that could be capable of verifiably and thoroughly defining the investment attractiveness of the region, which eventually may allow us to reveal the investment potential in question and to manage investment risks.

The investment attractiveness of a region is determined by comparison of two parameters reflecting the conditions in which investors’ activities take place: investment potential and investment risk. The amount of risks associated with investment activities is large, while uncertainty of their occurrence compels investors to evaluate the investment

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

potential of a region as uncertain, too. Investment potential is a weighted average of a number of factors, such as:

- the factor of natural resources potential, including sub-factors: the share of the region's population in the total population of the country, divergence of the regional value for population density from the national figure, in-place reserves of the main natural resources;
- the factor of labour resources potential, including sub-factors: the share of the working-age population of the region in the total working-age population of the country; divergence of the regional value for urban population from the national figure;
- the factor of economic potential, including sub-factors: the share of the region's industrial output in the total national figure, the share of regional construction/civil engineering put in place in the total national figure, the share of regional output of the main food products in the total national figure, the share of regional retail turnover in the total national figure;
- the factor of economic development levels, including sub-factors: the ratio of regional per capita industrial output to the national figure, the ratio of regional per capita value of completed construction/civil engineering projects to the national figure, the ratio of regional per capita production of the main types of agricultural products to the national figure, the ratio of regional per capita retail turnover to the national figure;
- the factor of economic activity level, including sub-factors: the ratio of regional growth of industrial output to the total national figure, the ratio of regional growth of the value of completed construction/civil engineering projects to the national figure, the ratio of regional growth of production of the main types of agricultural products to the national figure, the ratio of regional growth of retail turnover to the national figure; the ratio of regional unemployment levels to the total national figure;
- the standard of living factor, including sub-factors: divergence of regional values from the national ratio of per capita cash income to minimum wage; divergence of relevant regional values from the national ratio of average wage to minimum wage;
- the factor of regional financial standing, including sub-factors: divergence of regional values from the national per capita accrued tax, divergence of regional per capita value of received federal budget allocations from the national per capita value of paid federal budget allocations, the specific weight of the number of unprofitable enterprises in the region in the total number of such companies in the country;
- the factor of economic reform, including sub-factors: divergence of the regional value of per capita budget expenses on economic development of the country from national levels, divergence of the regional value of the number of active banks from the total national figure, the specific weight of the number of mixed and private ownership companies.

On the basis of the above facts we can determine the index of investment attractiveness of a region by means of comparison of two parameters reflecting the conditions under which investors are doing their business, i.e. the investment potential and the investment risk [5].

The investment potential of the region is formed of the following indices: natural resource potential, labour potential, economical potential, level of economical development, economical activity, public purchase power, status of regional finances, progress of economical reforms. The indices of investment attractiveness of the region are integral and are calculated as the sum of individual integral indices estimating the effect of group of factors or parameters. The indices are formed by hierarchical principle: individual indices integrate indices or parameters of the lower level.

The individual indices integrate indices or parameters of the lower level or parameters comprehensively reflecting main macroeconomical parameters of the region.

The peculiarity of the method being used is the possibility to use various parameters, including hardly comparable ones. The specific set of initial data is determined proceeding from the specified objective and the availability of the data.

Calculation of integral indices is based on comparison of development levels of the regions with level of development for Russia equated with 1. The values of indices in dimensionless units vary in the range from 0 to 2.

In order that the values of indices fall within the specified range the following conditions are checked during calculation of deviations of regional values of parameters used for calculation of integral indices from their values for Russia:

- in case of positive effect of parameter on the index value (the more the better): if the regional value is less than the value for Russia – the ratio of regional value to value for Russia is calculated; if the regional value is greater than the value for Russia – the ratio of the value for Russia to the regional value is calculated and the result thus obtained is deducted from 2;
- in case of negative effect of parameter on the index value (the more the worse): if the regional value is less than the value for Russia – the ratio of regional value to value for Russia is calculated and the result thus obtained is deducted from 2; if the regional value is greater than the value for Russia – the ratio of the value for Russia to the regional value is calculated.

In order to indicate the significance of the parameters included into index the specific weights of parameters are used. The sum of specific weights of all the parameters is equal to 1. The specific weight values are determined by expert analysis and can be changed depending on significance of one or another parameter at the given moment of time [1].

$$I_j = \sum_{i=1}^{n} (A_{i,j} / A_i) * d_i ,$$

where:

I_i – integral index of j-th region;

A_{ij} - value of i-th parameter for j-th region;

A_i - value of i-th parameter for Russia as a whole;

D_i - specific weight of i-th parameter defining its significance among other parameters used for calculation of the index, while:

$$\sum_{i=1}^{n} d_i = 100\%$$

This approach allows us to define a region's economic health in the situation of risk and uncertainty.

2.2 General index of investment potential

Having identified factors influencing investment potential and investment risk, we now have to choose mathematical instruments to assess it.

indicator of investment activity, for integration of indicators of capital availability, capital-labor ratio, yield on capital investment, average education level and performance into a general indicator of investment potential state, and also indicators of investment effectiveness in the region, is the multivariate average method [3,4]. This method has been widely applied for comprehensive regional assessments. Using it we can calculate the generalized factor index for each region. This index is a ratio of the indicator to the average national value taken as 1 or 100%, calculated by Formula 1:

$$k_j = \frac{P_j}{P_{cp}}, \quad (1)$$

where P_i is the actual value of the j-factor used for the assessment of investment climate, P_{cp} is the average value of the j-factor for a group of studied regions. The specific nature of this method is comparison of per capita regional factors under consideration (investments, yield on capital investment, average education level, etc.) with national average values for the same factor. As a result of the comparison we have normalized per capita values for these factors per region. To obtain more verifiable results we have to somewhat depart from the adopted method. It is necessary to calculate not the arithmetic mean of the used factors, but the length of a vector, whose projections onto the reference frame are the values of the factors taken for integral assessment. Calculation of the length of this vector is done by Formula 2 as follows (2) [6]:

$$V = \sqrt{A^2 + B^2 + C^2 ...} \quad (2)$$

The resulting vector is present in a *n*-dimensional system of coordinates, where *n* is the number of factors used. The length of the vector will be a characterization of the integral assessment of investment climate in regions, compared with the average national level. Further on, assessments per region are summarized as one integral indicator.

By ranging regions according to this integral indicator, we will be able to talk about objective, verifiable assessment of investment climate in each of them and about its rank among all other regions of Russia. This indicator allows us to compare variances in the levels of investment climate per region in addition to their individual ranks on this rating scale. Having only these ranks we cannot reveal to which extent one region excels other ones or yields to them, because when we range an attribute between two adjacent regions the variance may be both large of small; ranks do not reveal this.

3 SYSTEMIC NATURE OF INVESTMENT RISK

The rate of investment potential is influenced by investment risk, which is a combination of interrelated risk factors defined as the probability of loss and damage [7]. A loss/damage criterion for us will be the occurrence of events that determine the efficiency of investment process above the acceptable risk level. A risk factor is an accidental event or a group of events that are responsible for this type of risk. In other words, these are the so-called factors and effects of their interaction, which allow us to define that one risk event is produced by one or more risk factors that are damaging to the risk object.

Any risk can be presented as a system, by which word we understand a combination of risk factors with independent effects of their interaction. The investment realm, at the same time, is a closed continuous system of interaction of risk factors, whose structure, properties and management are to be studied. This points to the duality of system building in the investment domain and duality of risk factors influencing the ambiguity of investment results.

To manage investment risks we have to do analysis and assessment based on a range of principles, i.e. methodological, procedural and operational ones.

Methodological principles are defined as conceptual postulates; they do not depend on specific types of risk; these principles are: uniformity of risk types for all participants of investment process, positivity of risks (acceptability of their integral level), risk objectivity (integral monotonicity, disproportionality, transitiveness, additivity), integral nature and interrelation of risks.

Procedural principles are directly linked to the type of business, its properties and characteristics, accepted values and attitudes, specific cases. these principles are: risk discordance, varying risk perceptibility, dynamics and consistency of risks.

Operating principles are linked to the presence, verifiability, unambiguity of data and to instruments of their processing; these principles are: modeling and simplifying risks.

To analyze and assess risks the system research approach was used. All approaches to system research can be either analytical or synthetic, which in their turn brake down into: analysis – functional or structural, synthesis – emergent (that defines coherence of a system) or synergetic (co-acting, multiplicative effect). To reveal "emergent" properties of risk factors means to declare the emergence of new risk factors of interacting objects.

Having said all the above, we can now make a conclusion that application of the system-synergetic method forms a fresh view on the realm of investment in regional economies and opens new opportunities for investment risk assessment and management. The investment risk in a region is a weighted average of risk factors each one of which is, in its turn, a combination of sub-factors of risk. The significance and composition of sub-factors of risk for risk management are defined by regional policies and follow their changes.

Let us now identify the basic types of investment risk factors: economic, financial, political, social and legislative ones.

Having identified factors and risk factors that define investment potential and investment risk, how we have to choose mathematical instruments for the assessment. We consider investment attractiveness of a region from the point of view of the maximum investment potential and minimum investment risk.

4 LOGICAL STOCHASTIC MATHEMATICAL MODELS

Commonly known stochastic mathematical models used in the economics do not allow us to adequately and reasonably assess and minimize regional investment risk. The paper proposes application of logical stochastic mathematical models such as failure scenario, emergencies and catastrophes, structural models or graphs of risk, logical models of risk, stochastic models of risk, and critical points for emergency forecast.

In the above listed models an important role is played by permissible values for parameters that are, usually, chance variables. To build the models cited above, we have to solve the following tasks:

- building of a scenario/structural model of risk;
- defining of attribute-events and gradation-events;
- defining of groups of incompatible events;
- distribution of discretization of accidental gradation events;
- generation of random discontinuous distributions;
- building of a logical model of risk;
- orthogonalization of a logical model of risk;
- building of a stochastic model of risk;
- normalization of event probabilities;
- optimization of a logical stochastic model of risk.
- defining of associations between risk parameters Yad, Risk, Nad, Had.

Now let us consider methods and techniques of solving the above tasks.

Building of a scenario/structural model of risk.

We can use here both the success risk scenario and the failure risk scenario. Probabilities of success and failure have a simple dependence and complement each other up to 1. Constructively we have to emphasize failure and build/use the scenario and logical stochastic models of failure risk. A scenario may have a physical basis or be associative, it can define all or a limited number of unsafe conditions of an investment program. The scenario is presented as a graph.

Defining of attribute-events and gradation-events.

Probabilities of attribute events and gradation events are given or defined by statistical data by the frequency of use of gradation events in various conditions, or are defined as a result of solving the task of identification according to statistical data.

Identification of groups of incompatible events and distribution discretization of accidental gradation events.

Discretization of a random variable can be natural or artificial. For instance, a random variable Z_j for the "purpose of investment" attribute is discretized naturally by gradations such as residential housing Z_{j1}, equipment Z_{j2}, communications Z_{j3}, etc., while a random variable of "return on equity" Z_i, divided by gradation intervals $Z_{j1}, Z_{j2}, ..., Z_{j N j}$, is discretized artificially. In some cases, for instance for investment risk assessment, both natural and artificial discretization is used (the possible total sum of investment is divided by intervals). In all cases, gradation events for one attribute of investment or yield on equity comprise a group of incompatible events whereby the sum of gradation probabilities events is 1.

Generation of random discontinuous distributions.

To test logical stochastic methods of risk analysis and assessment, and for the purpose of teaching of logical stochastic risk models, we have to generate gradation events for an attribute with random discretized distribution; for instance, gradation events of attributes of investment, return on equity, the values of influencing variables and the efficiency parameter. Random discrete distribution is obtained by summation of a number of elementary distributions generated according to different laws. For elementary distributions we shall use, for instance, normal law distribution, uniform law distribution, trapezoid law, law of increasing/decreasing line, Weibull law, etc.

The method for building a random discrete distribution is as follows:

1. Using the chosen elementary distribution law for attribute Zj, generate randomly N values of the attribute within the range of its variation $\{Z_{j\ min}, Zj_{\ max}\}$.
2. Divide the obtained attribute values by N_j gradations.
3. Calculate frequencies-probabilities for these gradations by Formula 3.
4. Repeat steps 1 - 3 to generate the chosen elementary distributions, each of which also has N_j gradations.
5. Summarize the resulting various elementary distributions.

$$P_j = x_1 p_{1j} + x_2 p_{2j} + ... + x_k p_{kj}, \quad j = 1,2,..., N_j, \tag{3}$$

where:

$x_1, x_2, ..., x_k$ - values of weight of the elementary distributions whose sum is 1;

Pj - gradation probability of attribute j;

$p_{1j}, ..., p_{kj}$ - gradation probabilities of j elementary distributions.

Building of a logical model of risk.

A logical model of failure risk is written as a disjunctive or conjunctive normal form, i.e. as a logical statement with *OR, AND, NOT* operators, cycles and groups of incompatible events, but without brackets. A logical model of failure risk can be also written as an orthogonal disjunctive normal form or as a perfect disjunctive normal form. A logical model of failure risk defines all dangerous conditions of a system or a limited number of such.

Orthogonalization of a logical model of risk.

Orthogonalization allows us to proceed from a logical function of failure risk to a stochastic function of failure risk, in other words, from logical expressions to arithmetic expressions. The latter allow us to carry out qualitative assessment and to analyze risks.

Building of a stochastic model of risk

A stochastic model of failure risk is built after orthogonalization of a logical model of failure risk. A stochastic model of failure risk can define all dangerous conditions of a system or a limited number of such. This model allows us to carry out qualitative assessment and to analyze risks.

Normalization of event probabilities (conditions, states) is based on the assumption that their sum, by implication, is 1.

Event probabilities normalization is done in the following cases:

- while identifying (optimizing) a stochastic model of failure risk by statistical data for gradation events in groups of incompatible events;
- when there is statistical data for a limited set of system conditions or objects from the complete set of all probable conditions or objects;
- while building, by the Monte-Carlo method, models of a limited set of conditions (objects) from the complete set of possible conditions.

Normalization is done via dividing the probability of each event (condition) by the sum of probabilities of the event (condition) set under consideration.

Optimization (identification) of a logical stochastic model of risk.

When building a logical stochastic model of risk in systems containing groups of incompatible events, tasks of optimization of sets of objects and object conditions are solved. Optimization in an investment task means defining optimal shares of capital to be invested in the investment program. Optimization within the effectiveness task means defining of the weights of processes that influence the resulting process.

Defining of associations between risk parameters Yad, Risk, Nad, Had.

In systems containing groups of incompatible events the following risk-defining parameters are considered:

Yad - allowed value of effectiveness parameter;

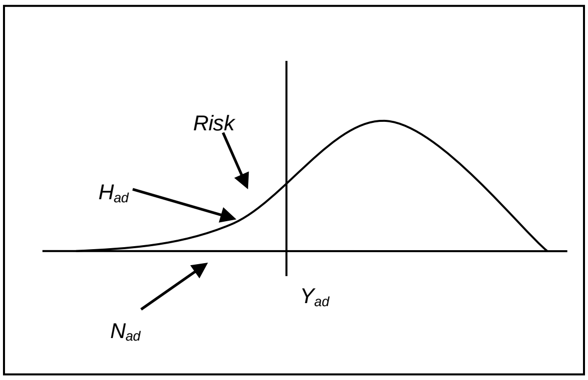


Fig. 1. Risk parameters in the distribution tail area

Risk - the probability of having the effectiveness parameter value that is smaller than permissible;

N_{ad} - the number of objects (object conditions) in the tail area of distribution of the effectiveness parameter;

H_{ad} - entropy of probabilities of objects (object conditions) in the tail area of distribution of the effectiveness parameter;

Calculation of a permissible value for output parameter Y_{ad} with the given value of *Risk* is a complicated algorithmic problem. Below we shall consider various methods of solving it.

1. Interpolation. We build a discrete differential distribution of the output parameter *Y.* For this purpose, its whole variance range is divided by N_y intervals (gradations). The probabilities *Pi* of the value of the parameter at chosen intervals are summarized. Then, an integral discrete distribution of the parameter У is build. After that we can calculate the permissible value Y_{ad} with the given value of *Risk,* using a linear interpolation formula.

2. Sorting. The sorting method is a simple and reliable method of calculation of the permissible value for an output parameter Y_{ad}. Value arrays of the Y_i parameter and its *Pi* probabilities from *i = l, 2, ..., N* values are sorted by the value of the output parameter $Y_{iв}$ in the ascending order. Then, for arrays already sorted, we have to summarize probabilities P_{yi} of parameter Y_i values until the given value of *Risk* is obtained. The last summands of the sum of the array of probabilities is corresponding to the output parameter value which we have to take as the permissible value of Y_{ad}. The complexity of sorting depends on the number of conditions *N* of the output parameter Y_{ad}; in practice the time spent on multiple optimization sorting is more or less acceptable.

3. Bipartitioning. The $[Y_{min}, Y_{max}]$ interval is repeatedly divided into two equal parts $[Y_{min}, Y_{1/2}]$ and $[Y_{1/2}, Y_{max}]$. For each of the parts, by way of summation, probabilities $P_i = P\{Y < Y_{1/2}\}$ and $P_2 = P\{Y > Y_{1/2}\}$ and the number of objects in parts N_1 and N_2 are defined. The part containing the value *Risk* is again bisected. The procedure goes on and on until the number of conditions in one part = 1 object. With *N* = 1000 objects, the search of Y_{ad} by bipartitioning proceeds threefold faster than sorting.

The N_{ad} parameter defines the number of conditions of the output parameter Y_{ad} that are in the tail of distribution, i.e. when $Y_i < Y_{ad}$. This is a very important risk characteristic because it is a whole and can be calculated to a precision of 1. From this follows that we can solve the problem of optimization, investment program risk assessment by using not the objective Y_{ad}, function, but its equivalent – the objective N_{ad} function.

Entropy H_{ad} is another characteristic of the distribution tail area (Shennon entropy). Degree of nonhomogeneity or diversity of sets of objects or conditions depends on the total number of objects in a set, on the number of different objects and their probabilities in this set.

To measure the diversity of objects or conditions of an object in the tail area we'll use the entropy defined by the expression

$$H_{ad} = -\sum_{i=1}^{N_{ad}} p_i i_n p_i, \tag{4}$$

where:

H_{ad} - entropy;

Pi - probability *i* of an object or the condition of an object in the tail area of distribution;

N_{ad} - number of objects or object conditions in the tail area. Summation is done for all objects in the tail area.

Entropy proves itself quite well as a measure of diversity in the most general case because it has the following features:

1. It becomes zero when occurrence of one element in a set is certain while for other elements it is impossible.
2. It has its maximum with a given number of different elements when occurrence of these elements is equally probable.

3. It increases when the number of elements in the set increases.
4. It has additivity properties, i.e. when a set of independent elements-events is joined into one, their entropy sums up and the result is the entropy of the joint set.

As has been proved by A.Y.Khinchin, entropy is the only function that demonstrates such properties. It should be noted that the logical stochastic theory of risk can be presented as a theory of integers with arithmetic operations of summation/division of whole numbers.

Let us now consider the method of building logical-and-probabilistic risk models containing a group of incompatible investment events/cost-efficiency events, used for the management of social and economic processes.

Logical-and-probabilistic risk models containing a group of incompatible investment events. A logical-and-probabilistic risk model for a securities portfolio is build by introducing discontinuous distributions (gradations) of ROI for assets Z1,…, Zj,…, Zn (a random distribution). Gradation events for each of the assets will form a group of incompatible events. The task of choosing an optimal portfolio lies in the process of defining, on the basis of statistical data concerning the assets' ROI dynamics, of appropriate capital shares x1, x2,…, xn invested in the assets. The optimization criteria by a logical-probabilistic VaT (LP- VaR) is the maximum acceptable ROI of a portfolio Y with the specified Risk value. Portfolio management is done by way of changing capital shares x1, x2,…, xn in the assets, and by the contribution of gradation events in the distribution tail-area of the portfolio Y's ROI [7].

A logical-and-probabilistic risk model containing a group of incompatible events linked to the cost-efficiency problem. According to James J. Heckman, the Nobel Prize winner, the cost-efficiency parameter for management of social economic processes depends on the influencing variables Z1,…,Zj,…,Zn, having different nature and dimension; it also has multivariable distribution. To solve the problem we have to make a transition from the continuous to discontinuous distribution of random variables. For this purpose, the influencing variables and the cost-efficiency parameter are broken up into intervals N1,N2,…,Nj and Ny which are considered to be gradations. The problem of optimization by statistical data is formulated as the problem of defining appropriate weights x1,x2,…,xn of the parameters that influence the Y's efficiency. After that we introduce the following criteria: the acceptable value for the risk and cost-efficiency parameter; our goal here is to obtain it at its smallest. Risk management is done on the basis of the values of weights x1,x2,…,xn and the contribution of gradation events in the tail-area of the distribution of cost-efficiency parameter Y [7].

Logical-and-probabilistic models can be used for the development of scenarios of failure, emergency, disasters/accidents at industrial enterprises, which will allow us to evaluate their stability.

5 CONCLUSION

Attracting investors to the Russian market is a hard task because attempts to assess regional investment activities have been rather rough than accurate. Unified approaches to interpretation and composition of indicators are inexistent. The worst problem here is that there are no unambiguous assessment of investment climate and risks of a region. By doing an integral assessment of investment attractiveness of regions, by reducing all indicators to a complex one, by ranging regions according to this complex indicator, we will be able to talk about objective, verifiable assessment of the investment climate in each of such regions and about its rank among all other regions of Russia. This indicator allows us to compare variances in the levels of investment climate per region in addition to their individual ranks on this rating scale. Having only these ranks we cannot reveal to which extent one region excels other ones or yields to them, because when we range an attribute between two adjacent regions the variance may be both large of small; ratings or ranks do not reveal this. Logical stochastic mathematical models of investment risk assessment allow us to supplement and refine the above analysis. This approach will allow a potential investor to take an informed decision with a minimized risk of getting poor investment results. As a conclusion it should be noted that the method of logical stochastic risk assessment, proposed in this paper, was applied to justification of risk assessment during development of an investment program for the North-western Federal District of the Russian Federation.

6 REFERENCES

[1] Bard E.S., Buzulukov S.N., Drogobyckij I.N., Shepetova S.E., Investicionnyj potencial Rossijskoj jekonomiki. Moskva, Jekzamen, 2003, S. 320, 124-140. (The Investment Potential of Russia's Economy, pp. 124-140, 320).

[2] Gubanova E.S., 2004, Development and methods of implementation for regional investment policies. Author's abstract of a dissertation for the degree of Doctor or Economics. St. Petersburg, 32, 4-5.

[3] Kuznezov S.V., 2003, Investment potential of a region: assessment and implementation methods. St. Petersburg, 186, 76-78.

[4] Lukmanov Ju.H., 2003, Regional investment management, St. Petersburg: Nauka, 165,93-98.

[5] Nikolova L.V., Upravlenie investicionnymi riskami. Avtoreferat dissertacii na soiskanie uchenoj stepeni kandidata jekonomicheskih nauk, Sankt-Peterburg, 2004, S. 16, 4-5. (Author's abstract of a dissertation for the degree of PhD in Economics. Investment Risk Management, pp. 4-5, 16).

[6] Pushinin A.V., 2006, Development and assessment of investment climate of a region with regard to influences from physical and human capital (using data from the North-western Federal District of the Russian Federation). Author's abstract of a dissertation for the degree of PhD in Economics. St. Petersburg, 24, 15-16.

[7] Soloshenzev E.D., 2006, Risk management in business and engineering based on scenarios and logical stochastic models. Edition 2, St. Petersburg: Publishing house "Business-press", 530, 280-283.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

5.2 Requirements on the engineering of advanced standby strategies in automobile production

D. Wolff [1], L. Hundt [1], S. Dreher [1]

[1] inpro Innovationsgesellschaft für fortgeschrittene Produktionssysteme in der Fahrzeugindustrie mbH, Berlin, Germany

Abstract

A key challenge in manufacturing industry within the next years is to reduce and optimize energy consumption of production systems without affecting productivity. To adress this problem, different approaches are discussed, such as smart grids, or utilization of more energy-efficient machine components. A new approach on shop floor level is to optimize production control strategies, to power down inactive machine components during non productive phases. To fully exploit this potential, it is necessary to integrate the planning of the required control systems into all phases of the engineering process. This paper presents a concept for the integrated engineering of these new applications by evaluating planning tools, methods and data models regarding their suitability to implement the concept of advanced power down and restart concepts. In conclusion, requirements on these tools, methods and data models are defined, to empower them for optimal support of the future engineering process.

Keywords:
Engineering Process, Standby Control, Energy Efficiency, Engineering Data Models

1 INTRODUCTION

1.1 Challenges

A current challenge in manufacturing industry is to increase energy productivity without adverse effects on output, availability and operational robustness. It is a strategic objective ever more recognized in industrial production to systematically save energy related cost and to generate competitive advantage by rationalized use of energy and reduced CO2 emissions. [1]

Aside from the energy oriented planning of products, processes and resources at the early stage, significant potential is attributed to energy oriented production planning and scheduling in the operative stage. Here, efficiency gains may be harvested by 'energy-sensitive control of material flows, machines and peripheral systems' in production systems. [2] As one aspect of this, the reduction of energy demand during nonproductive phases in production represents a promising approach. [3] While significant potentials have, among others, been identified in the fields of machine tools and body in white [4], [5] the problem of efficiently engineering dynamic operative manufacturing system control systems has not been sufficiently solved, especially when taking into account later implementation in industrial control systems.

Digital support for the design and implementation of control strategies and of control systems for an energy oriented production therefore remains open to discsussion. In current established practice, control system engineering does not sufficiently consider energy efficiency as a planning objective. To address this deficit, this paper presents a new approach for designing, optimizing and implementing production control strategies by integrating digital design and validation of these strategies into engineering.

1.2 Vision

To ensure a sustainable success of energy management, planning and control must be linked. Practicable concepts for the integration of digital methods are required, in order to evaluate and optimize energy efficiency of production systems. This must firstly integrate digital models, methods and tools for control system design and operation, in order to realize energy optimized production planning and scheduling and production control. Secondly, it must integrate a concept for energy oriented control system engineering.

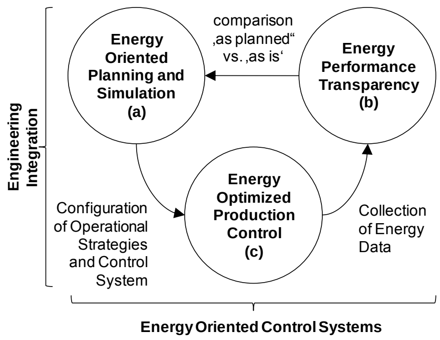


Figure 1: Integrated Key Applications.

This leads to a demand for three integrated key applications for energy oriented production control systems, as shown in Figure 1. First, planning and simulation applications integrating energy efficiency aspects must analyze the production systems in question to identify and validate improvement opportunities. Second, transparency with regard to both energy and production performance must be facilitated by intuitive access to the collected energy data, e. g. by innovative visualization methods. Third, energy optimized production control systems must implement efficient control strategies on different automation levels.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

2 ENGINEERING OF ENERGY OPTIMIZED CONTROL STRATEGIES

2.1 Advanced Standby Strategies for Automated Control of Energy Saving Modes

During idle phases or during interruptions of production flow, a temporary transfer of machines, machine components or even entire manufacturing line sections into an Energy Saving Mode (ESM) of operation may tap economic potential. This may be implemented in different ways, e. g. as a temporary machine shut down during scheduled breaks, as a slowed mode of operation during phases of low utilization, or as power down procedures into 'standby' or 'sleep' modes during unplanned disruptions. For powering down a machine or device, multiple energy levels may be feasible. [6]

Similar as with consumer devices, ESM for industrial use represents a machine state where components required for quick power up and restart into production mode stay active, while nonrequired components are temporarily switched off and disconnected from the supply networks. During the resulting energy reduced machine state, certain restrictions on operative responsiveness and availability, e. g. powering up within a certain time, may apply. The duration of the energy reduced state and the transitional state may be called Energy Saving Phase (ESP). Figure 2 shows the principle of this behavior for a machine that consumes electrical power.

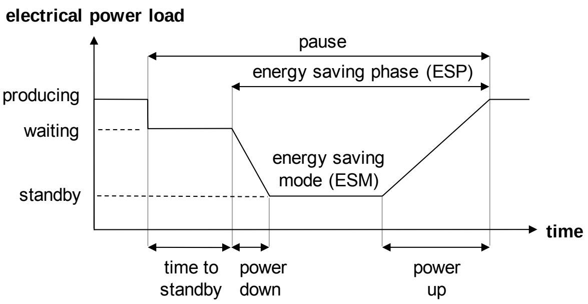


Figure 2: Electrical Power Load during Switching into ESM.

To put machines into ESM requires control mechanisms, composed of both hardware components (physical control systems, able to control the energetic behavior of machine components) and a processing logic (based on a decision strategy). Such an Energy Saving Control (ESC) may be located on different automation levels, either in a software application (e. g. on ERP or MES levels) or in industrial control systems software (e. g. on PLC or PAC levels), or as a combination thereof. Implementation of the necessary software algorithms may be built on existing automation systems hardware by integrating new protocols, such as PROFIenergy. [5] The required logic, formulated in an Energy Saving Strategy (ESS), must be the output of energy oriented engineering. These strategies may be labelled 'advanced' if able to process additional information from the production process and its ambient conditions in an anticipatory way, so as to adaptively react to dynamic energy demand and to accordingly control the ESM. Such advanced ESS can take into account e. g. material flow information on line level, thereby dynamically identifying situations advantageous for power down during low utilization conditions or failure situations, as shown in [6]. Since these strategies may be installed on different factory levels, several automation levels must be addressed. As shown in [8], various 'energy control loops' can be implemented to control the energy flow in production autonomously, requiring new information flows and communication mechanisms. This represents a future challenge for the implementation of industrial automation systems, able to realize those energy optimized control strategies. Obstacles to efficient information sharing and reuse in the field of Sustainable Manufacturing have been stated: Lacking standards for information representation, lacking interoperability among engineering applications, and lacking consistency across information modeling approaches. [9] It follows that requirements to innovate the engineering processes and to accommodate effective ESS design and implementation need to be identified. [9] Generic requirements should therefore be known and formulated, in order to adapt traditional engineering processes.

2.2 Involved Engineering Steps

To implement an ESC for ESS all engineering phases within the engineering processes of the digital factory [10] have to be adapted to the new requirements. Energy efficiency has to be integrated into plant design, into the mechanical and electrical construction steps, the programming, the plant manufacturing and assembly, the virtual and real commissioning phases as well as the ramp up stage (Figure 3). First basic decisions for an energy optimized plant layout thereby can be taken in the design phases. Afterwards, in the successive realization phases, results from the design phase may be built on to implement new control concepts like ESCs.

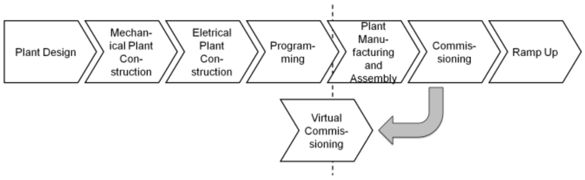


Figure 3: Engineering Steps according to [10].

2.3 Relevant Engineering Information

In [11] the concept of 'planning objects' is introduced. According to this, one single information object may be used to combine all relevant information to a real existing object. This can take place along the entire planning and realization process. Different levels of automated production systems can thus be modelled by aggregation of lower level objects into higher level objects.

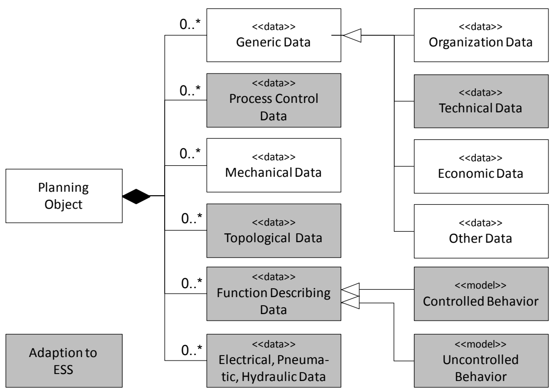


Figure 4: Information Model for ESS.

The main advantage of this concept is to provide a specific view on a planning object for each engineering task. This view only includes the relevant models and corresponding information. For the future task of designing ESS, a new engineering view therefore must be provided. Different data views that belong to a planning object must be adapted and extended, as shown in Figure 4. Thus, a distinct new ESS view can be defined. To integrate all necessary information for the design of ESS into the concept, at least five informational entities must be included in the different data blocks of a planning object. These are:

1. The physical manufacturing area involved, defining the machines and components affected by power down or shut down, must be enclosed in the view.
2. The conditions for power down and power up, such as logical conditions or time conditions, should be specified both on line level (i. e., for interconnected machines) and on machine level (i. e., for machine components).
3. The required shut down sequences, both on line level (e. g. for sequential machine shut down, resulting from informational interaction between machines and/or transport and handling systems) and on machine component level (i. e., the specific power down sequence), must be included.
4. The transition times for the transfer into and out of ESM.
5. Boundary conditions, such as technical restrictions for the maximum allowed frequency of ESM per hour in order to limit component wear out, or even conditions when ESM should be omitted, might also be included in the view.

As this list is noncomprehensive, this view may be complemented with further information when necessary.

2.4 Relation of ESS information and engineering steps

Figure 5 shows this allocation of the previously stated informational entities to the relevant planning phases. For the application of control systems implementing ESS, the specific information (a) has to be processed in different engineering steps (b). For example the ESS relevant topology data are used in all phases from plant design to plant manufacturing and assembly. In contrast to this, the functional description data are only used in later stages of the process.

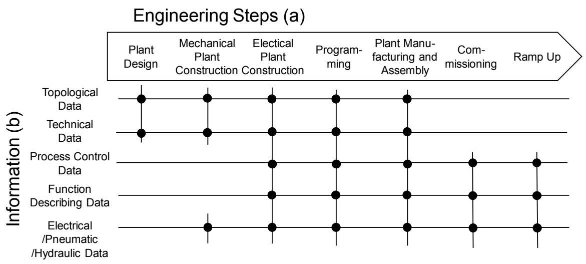


Figure 5: Information Flow between Engineering Steps.

3 GENERAL REQUIREMENTS

3.1 BWM Classification

Within the planning process of automation systems, each engineer needs different auxiliary means to execute his specific engineering tasks. In [12] these resources are classified into three categories, called ‘BMW' classification:

- B (german: ‚Beschreibungsmittel‘) – Data models provide means of formal description.
- M (german: ‚Methoden‘) – Methods.
- W (german: ‘Werkzeuge') – Tools.

The first category includes both engineering models and data models. These models shall be able to contain all relevant information needed to execute an engineering method. This might be information regarding a single object, a relation between objects or the formalized behavior. The second category includes methods that describe, in a systematic fashion, necessary activities to obtain valid results in the corresponding engineering step. The third category contains tools supporting method execution. These must offer specific functions to the engineer that can be used to implement the methods.

All of these categories have to fulfill certain general requirements to support the objective of implementing ESS. A collection of these new requirements is presented in the following subsections.

3.2 Data Models

Requirements on engineering data models can be subdivided into two subgroups, the first related to static information models and the second to the description of the dynamic behavior of the energy optimized system.

Requirements relevant to static models are:

- Informational descriptions of energetic machine states that are coherent with nonenergetic operational states.
- Attributes to system states and transitions that relate to energy use.
- An energy view extension, assuring that energy demand and consumption can be derived from the model.
  - Extensions for data handling and information management, including metadata management.
  - Known energy consumption behavior, such as energy profiles.
  - Restrictions, such as limits for the frequency of occurrence of ESM.
  - Models to maintain relevant energy related data over the production system lifecycle, so that informational entities can be connected over time and over successive engineering and implementation steps.
- Model parameters for dynamic analysis and experimentation.
  - Requirements regarding energy use, e. g. admissible values for peak load.

Requirements relevant to dynamic behavior are:

- Adapted dynamic behavioral descriptions of machines and components to include the energetic behavior, such as models to describe the switching and operating behavior of energy optimized automation systems as described in [13].
- Interaction and conflict resolution rules between energy efficiency objectives and other efficiency targets.
- Formalized description of ESS, e.g. concerning the implementation as a reactive, a prospective or a combined logic. [7]
- Interaction models for the communication of energy related information inside the production system.

3.3 Methods

In the category of methods, the following general requirements can be stated:

- Procedures to facilitate model building for energy calculation, including approaches to adopt and reuse existing models for energy analysis so that no new models must be build from scratch (or only if the anticipated gain of knowledge justifies the effort).

- Ability to analyze energy efficiency at different levels of abstraction and granularity. [9]
- Efficient ways to prepare input data for use in dynamic models, and procedures for efficient experiment design and execution and for result documentation. This includes the ability to transform input information into computation-friendly forms for analysis and optimization. [9]
- Quantified uncertainty analyses must become part of the verification and validation procedures. [9] This requires suitable validation and risk measurement indicators for scenario evaluation.
- Intuitive ways to support the quick evaluation of generated results and output data, such as innovative visualizations.
- Ability to couple modelling methods with a suitable portfolio of optimization methods and algorithms.
- Integration of requirements from control systems design and automation standards.
- Ability to implement the control as a central or autonomous control on a certain automation level.

3.4 Tools

In the category of tools, a number of requirements can be formulated:

- Interoperability of systems needed for energy efficiency assessment and aggregation of suitable metrics. [9]
- Support for energy views, integrating energetic parameters and models for energetic behavior.
- Efficient storage and exchange of relevant information. [9]
- Functions to combine static energy information and dynamic energy behavior models.
- Functions to calculate aggregate and specific energy demand and consumption from the models.
- Integration of or coupling with suitable optimization algorithms.
- Appropriate human machine interfaces.

3.5 Adapted Business Processes

Additional to the requirements on the models, methods and tools, the business processes have to be adopted for an economic and verified implementation of ESS. Following challenges regarding the process should be considered:

- Descriptions for operative procedures, e. g. adapted planning processes.
- New factory acceptance processes.
- New testing methods for ESS and ESC implementation during ramp up.
- New operating strategies.
- Adopted development and implementation milestones, including new decision and checking points and quality gates.
- Adapted description standards for energy aspects.
- Adapted specification sheets and functional specification.
- Adapted parameters for purchasing departments.

Though this list of changes in the business processes, just as the engineering information stated above, is noncomprehensive, it illustrates the complexety of nontechnical restrictions that must be considered in the introduction of ESS into planning processes.

4 APPLICATION CASE: STANDBY STRATEGIES IN AUTOMOBILE PRODUCTION

Subsequently, an exemplary approach for the stated principles and procedures will be presented. The underlying assumption is that the design of ESS can be supported by digital models. These can be used to analyse the potential, to optimize the decisional logic and finally also to implement the operational control logic in industrial automation systems. Support in different fields of activity is required, such as material flow analysis and energy flow analysis, combined optimization of both, and in implementing the strategies into control systems. Figure 6 provides an overview over these fields in the form of a method matrix. Envisioned result of this approach is the generation and formal description of premises for power down and restart concepts. This provides the basis to program and implement ESCs.

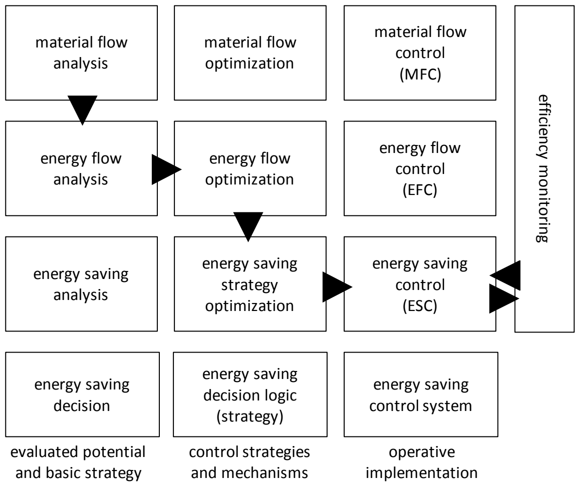


Figure 6: Method Matrix for ESC.

4.1 Production System Model Building

Discrete Event Simulation (DES) is an established method of the Digital Factory [10]. It represents dynamic processes of a system within an experimental model [14] and may typically be used to analyze material flows. Taking the view of 'dynamic processes' as interconnected material and energy flows, these simulation models may be augmented by energy flows to help calculate and analyse the energy consumption of complex production systems.

A widely followed approach in industry is to use standard libraries for digital model building to reduce modelling cost. Providing energy modules as part of these libraries allows to significantly reduce the modelling effort and to increase the reuse of existing simulation models. Implementation of this approach has been demonstrated on established simulation tools to assure conformity with existing processes of automobile manufacturing. [15] An example of this is the adoption of the modeling and simulation tool 'Plant Simulation' (an established standard tool for material flow simulation with major German automobile manufacturers and suppliers) to the analysis of energy consumption, as shown in pilot studies in component manufacturing and body in white manufacturing. [7], [15], [16], [17]

4.2 Production System Analysis

The first question of analysis amounts to a quantification of non value adding energy consumption and of the resulting saving potential for implementing ESM. To start with, ESM is only viewed on machine level and component behavior inside the machine is not considered. Following this approach, ESS are simulated based on the overall material flow in the system on manufacturing line level. [7] To implement this, the model objects representing machines are put into ESM and the material flow is stopped in certain predefined situations, i. e., when defined conditions are met. These conditions must be specified in the model. In this manner, selected control strategies that are most feasible for operation can be deduced from the model in the course of experiments.

Results of this analysis are:

- Occurrances of ESM at each simulated machine in the manufacturing system with given simulation premises. This can, for example, be used to show that defined standby frequency limits are not exceeded.
- Quantified energy saving potentials for the simulated machines with given production premises, e. g. product mix, setup time, tact time, failure scenarios, based on a given standby configuration. The latter may include the definition of allocated machines, of transition times, of material flow conditions, the dependencies between components, machines, transport and handling systems and control systems, as well as the specified power loads in different energy levels.
- Improved understanding of the effects of different standby parameters, such as transition times, and of specific energy consumption in ESM, both on the overall energy consumption and on the production output.
- The interacting effects of the different strategies applied, and a more complete understanding of the energy reducing effects of the strategies, and on their effects on output, on the utilization of machines and conveyor systems and similar performance measures.

Still, material-flow-oriented control strategies can be analyzed even without coupling the simulation model with a physical control.

4.3 Optimization

Innovation oriented production systems must ensure optimum productivity while considering various restrictions in the planning and execution of production processes. [18] With regard to energy saving production systems, the purpose of optimization therefore must be to identify optimal technical design structures and operating points for the engineering and implementation of ESS.

A typical overall optimization issue is to assure that the execution of machine ESM does not affect operational productivity and output requirements are met, while reducing product-specific energy consumption. Further aspects may be integrated into analysis, such as disturbance reactions or dynamic failure behavior resulting from recurring power down and power up transitions. In connection with the achieved energy reduction, the particular standby parameters (see 2.3) under the above mentioned restrictions can therefore be subjected to optimization. The respective potential can be located in different areas, as described below.

Economic Feasibility of ESS

Overall, the feasible energy saving potential over the production system lifecycle must be made transparent and confronted with the predicted cost for design and implementation of the required control systems in the engineering process. To the degree that ROI is anticipated, up front costs into necessary hardware and software systems can thus be justified. For this, invest into necessary hardware components must be known.

Technical Feasibility of ESS

Achievable energy savings must be balanced against known and suspected technical and operational risk. This comprises risk to system and process reliability, e. g. incurred by instable machine behaviour due to new complex control systems interactions. Another risk is the additional machine wear that is caused by frequently powering down and successively starting up the production hardware and control systems. Further, risk to productivity results from nontimely start up procedures, from increasing sensitivity to failures and from the resulting need for additional maintenance. Though hard to predict, the evaluation of these critical issues within the context of saving energy provides a promising field for optimization.

Specific ESS Configuration

As listed in 2.3, various configuration parameters, e. g. transition times or power down sequence, determine the specific characteristics of the standby behaviour of a machine. The identification of favorable parameter values may be optimized and balanced against the anticipated engineering effort that is necessary for developing and implementing components with the required behaviour.

Finally, machine based strategies may be evaluated against material flow oriented strategies as well as in combination of both, as [7] has shown,

Standby Application and Scaling of ESS Deployment

This issue concerns the question a) which machines respectively production areas should be subjected to ESM in general and to what degree they can contribute to overall energy savings, b) which strategies should be applied to which machine and c) on a technical level, the configuration of an optimum number of specific ESM and energy levels per machine.

A further question may be addressed by determining suitable manufacturing conditions under which ESS may favourably operate, with the prospect of implementing dynamic concepts where the validity of the ESS changes over time, i. e. the ESS acts only during specific periods.

Another approach is to minimize power down and shut down occurances respectively due to technical insecurities, in favor of slowed operation. In this context, rules for allocation of these strategies, their temporary disablement or even for dynamic switching between different strategies may be tested for optimality regarding the above mentioned targets. This can include the question where actual automated control is necessary and where maybe human interaction procedures can sufficiently assure energy reduced machine modes, as during shift breaks or scheduled pauses.

4.4 Transfer to Field Control Concept

In a final step, the results of the optimization phase have to be transferred from ESS to field control concepts. Here, several challenges have to be solved:

- The engineering data exchange towards PLC programming has to be supported.
- ESS have to be implemented into control programs afield.
- The specific field communications between the ESC and the different single devices that can be switched into ESM on different energy levels have to be designed.
- ESS have to be implemented such that after switching between different ESM or energy levels, all single devices as well as the entire line or plant still works correctly.
- This part of the engineering process has to be optimized for future projects.

For these challenges prototypical implementations currently exist. The data format AutomationML is used to organize the data exchange. Implementation according to the PROFIenergy specification is a means to realize the field control system and the communication between the devices. For validation new energy specific simulation models have to be implemented in tools of virtual commissioning. Further, a common approach must define libraries for engineering process optimization and reuse of project results.

5 SUMMARY AND OUTLOOK

Significant potential may be attributed to energy optimized control of production systems. Advanced control mechanisms may be used to implement intelligent strategies for powering down and restart machines and components during nonproductive times. The logical decisions taken by the operative control systems to perform this kind of behavior on shop floor level must be formulated in strategies to facilitate the predictive analysis and optimization as well as the efficient implementation of energy optimized control. This leads to a demand for the validation of these control strategies in early planning stages and for the support by digital models, methods and tools. Integrated concepts are needed to innovate the engineering process accordingly. This paper has stated a view on the general requirements that should be fulfilled to arrive at this objective. Concluding, in an exemplary pass through the consecutive steps of production system model building and analysis, optimization and, finally, transfer into the field automation concept, selected challenges are stated that govern the current practical engineering process.

6 REFERENCES

[1] DIN Deutsches Institut für Normung e. V. (Hrsg.): Energiemanagementsysteme - Anforderungen mit Anleitung zur Anwendung (ISO 50001:2011); Stand Dezember 2011.

[2] Neugebauer, R.; Putz, M.: Schlegel, A.; Langer, T.; Franz, E.; Lorenz, S.: Energy-Sensitive Production Control in Mixed Model Manufacturing Processes. In.: Leveraging Technology for a Sustainable World. Proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California at Berkely, Bekerley, USA May 23-25, 2012, pp. 399-404

[3] Duflou, J.; Sutherland, J.; Dornfeld, D.; Herrmann, C.; Jeswiet J., Kara, S.; Hauschild, M., Kellens, K.: Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals, Manufacturing Technology 61 (2012), pp. 587-609.

[4] Jäger, A.; Maloca, S.: Dokumentation der Umfrage Modernisierung der Produktion 2009, Fraunhofer ISI, Karlsruhe 2009. In: Schröter, M.; Mattes, K.: Bewertung der wirtschaftlichen Potenziale von ressourceneffizienten Anlagen und Maschinen. Innovationsplattform Ressourceneffizienz in der Produktion. 03/2011.

[5] Klasen, F.: Profienergy – Die gemessene Einsparung in der Produktion. In: computer-automation.de (2011) 5/11.

[6] PI Whitepaper: The PROFIenergy Profile. PROFIBUS Nutzerorganiastion e. V. (PNO), Version 1.0, March 2010.

[7] Wolff, D.; Kulus, D.; Nagel, J. : Simulationsgestützte Bewertung von Energiesparstrategien. Berichte aus der inpro-Innovationsakademie, ZWF Zeitschrift für wissenschaftlichen Fabrikbetrieb, 03/2013 Jahrg. 108 (2013), pp. 103-108.

[8] Verl, A.; Westkämper, E.; Abele, E.; Dietmair, A.; Schlechtendahl, J.; Friedrich, J.; Haag, H.; Schrems, S. : Architecture for Multilevel Monitoring and Control of Energy Consumption. Glocalized Solutions for Sustainability in Manufacturing, 2011, pp. 347-352.

[9] Shao, G.; Riddick, F.; Lee, J. Y.; Kim, D. B.; Lee, Y. T.: A Framework for Interoperable Sustainable Manufacturing Process Analysis Applications Development. Proceedings of the 2012 Winter Simulation Conference.

[10] VDI-Richtlinie 4499 Blatt 1: Digitale Fabrik – Grundlagen. VDI-Verlag, Düsseldorf 2008.

[11] Hundt, L.: Durchgängiger Austausch von Daten zur Verhaltensbeschreibung von Automatisierungssystemen. Dissertation, Logos Verlag Berlin GmbH, 2012.

[12] Schnieder, E.: Methoden der Automatisierungstechnik, Vieweg Verlagsgesellschaft, 1999.

[13] Mechs, S.; Lamparter, S.; Peschke, J.: Start/Stop Mechanisms in Industrial Automation Systems for Energy-efficient Operation [11] Mechs, S.; Lamparter, S.; Peschke, J.: Start/Stop Mechanisms in Industrial Automation Systems for Energy-efficient Operation; In: Automation 2013 - Der 13. Branchentreff der Mess- und Automatisierungstechnik : Kongress Baden-Baden, 13.-14. Juni 2012. Düsseldorf: VDI Verlag.

[14] VDI-Richtlinie 3633 Blatt 1: Simulation von Logistik-, Materialfluss- und Produktionssystemen – Grundlagen. Verein Deutscher Ingenieure, Düsseldorf 2010.

[15] Wolff, D.; Kulus, D.; Dreher, S.: Simulating Energy Consumption in Automotive Industries. In Bangsow, S. (Ed.): Use Cases of Discrete Event Simulation: Appliance and Research, Springer Verlag, Mai 2012.

[16] Kulus, D.; Wolff, D.; Ungerland, S.: Energieverbrauchssimulation als Werkzeug der Digitalen Fabrik. Bewertung von Energieeffizienzpotenzialen am Beispiel der Zylinderkopffertigung. ZWF Zeitschrift für wissenschaftlichen Fabrikbetrieb, 09/2011 Jahrg. 106 (2011), pp. pp. 585-589.

[17] Jungnickel, F. ; Schulz, S. ; Konopka, F. ; Peschke, J., Kaliamoorthy, C. S. : Fortschritte in der Produktionsplanungs-Software : Kombinierte Energie- und Materialflusssimulation am Beispiel einer Türfertigungsanlage im Automobilbau. Proceedings of the 6. Fachtagung Energieeffiziente Fabrik in der Automobilproduktion, München, 20.02.2013.

[18] Spur, G.; Esser, G.: Innovation, Produktion und Management. Carl Hanser Verlag, München 2008.

5.3 Drivers and barriers to implement sustainable manufacturing concepts in Sri Lankan manufacturing sector

A.K. Kulatunga, P. R. Jayatilaka, M. Jayawickrama
Department for Production Engineering, University of Peradeniya, Sri Lanka

Abstract
Sri Lanka promotes manufacturing sector without much concern on environmental and social problems as one of the driving forces for the economic prosperity. This has aggravated number of issues and this has lead to adapting of some sustainability related initiatives in local manufacturing sector. However, majority of them function independently with fix boundaries. Conversely, there are some hindrances to implement the sustainable manufacturing concepts as a one comprehensive solution. This research intends to investigate the motivators and barriers to adapt sustainable manufacturing concept to overcome current issues faced by the manufacturing industry. An evaluation criterion was developed based on some of the popularly used guidelines and sustainability options available in number of sub domains. Results highlights the main motivators plus common and cluster specific barriers to implement sustainable manufacturing in local industry. These outcomes can be easily considered for the policy development purposes in developing countries in future.
Keywords:
Drivers and barriers for Sustainable Manufacturing, Policy making, awareness of sustainability, manufacturing plant sustainability, triple bottom line in sustainability

1 INTRODUCTION

With the opening up of its economy in the early 1980's, Sri Lanka as a country has been striving to develop its manufacturing industry as one of the main foreign income earners and to provide employment for the locals. In order to facilitate this policy, successive governments have even developed separate industrial and export processing zones, with most of the infrastructure facilities needed for the manufacturing sector. Although successive governments facilitated to develop manufacturing sector over the years, they could keep apply stringent measures to minimize environmental and social impacts, which are common problems associated with the development and expansion of the industry. Environmental pollution, industrial waste management, and exploitation of workers and health and safety of workers are some of the emergent problems. Since policy makers prime objective is to provide employment for locals and to promote foreign direct investments for establishment of industries, they often do not pay due concern to environmental and social problems which arise as a consequence of these initiatives.

Conversely, due to the lack of awareness of the community there is not much resistance or protest towards poor management of these industries or even to pressurize policy makers to adapt stringent measures to scrutinize the sustainability issues of the manufacturing sector. However, few manufacturing industries have adapted certain sustainability options within their organizations, with the awareness they receive from foreign business partners or due to the market pressure from environmentally conscious customers of foreign countries. Further, there are several promotions initiated again from foreign donor agencies, which motivate certain industries to align their practices towards Sustainable Manufacturing (SM) directions. These initiatives are becoming famous among the industrialists due to the recognitions they can gain in the form of annual awards (NCPC awards [1], Geo Cycle awards [2] etc.) The same strategy is currently being adopted by government authorities as well, with the aid of foreign funding to give some recognition annually in the form of green reporting initiatives (Green awards CEA [3]). However, both of these initiatives are limited to the environmental domain of sustainability as their mode of evaluation and do not consider specially the social aspects into account. Further, these schemes only look at the problems surfacing and do not go into the manufacturing processes when they evaluate organizations for these awards. When considering about sustainable manufacturing options (SMO), it is very rare to find any ministry or authority related to industries having a separate and dedicated unit to promote these concepts. There is also no evidence that relevant government authorities are aware of the concept "Sustainable Manufacturing". In addition, most of the local tertiary education programs do not have separate subjects such as Sustainable Manufacturing. However, certain industries have been changing their processes towards green energy options mainly due to the economic benefits than social and environmental benefits. Even government has taken steps to establish a separate unit (Sri Lanka Sustainable Energy Authority [5]) to popularize renewable energy among the industrialist in the recent past.

Although there are a few published researches in some of the sub-domains of sustainable manufacturing in the recent past [6, 7, 8 and 9] it is very rare to find any research in the direction of SM. Further, there is no research or any government or privately involved project to investigate the pros and cons or motivating and de-motivating factors to move in the direction of sustainable manufacturing. This research is carried out In order to fill this gap and thereby to develop a generic model to evaluate plant SMO, and it can be used to bring in potential SMO's to surface in addition to filling the present vacuum available within the country. Further this study will be useful when developing future policies not only for the Sri Lankan context but for most developing countries as well. The rest of the paper is arranged as follows; Section 2, explains the methodology used in this research, followed by the case study and the results in Section 3. Discussion on the outcomes of the research is presented in Section 4 while conclusion is given in the Section 5.

2 METHODOLOGY

The main obstacle to identify motivational and de-motivating factors towards implementing sustainable manufacturing practices in the local industry arises in a situation of how to recognize potential options depend on the nature of the industry. There are significant deviations available from different manufacturing sectors with respect to one SM option. Therefore, it is very important to first identify all possible SM options irrespective of the sector considered, and later to develop a generic model consisting of all the SM options. In turn, this type of model will assist to identify reasons behind implementing or not implementing SM options if we go by the SM options available in the generic model for manufacturing plant sustainable Manufacturing options (SMO). Therefore, initially, a generic model was developed to specify all possible SMO's that is applicable for any manufacturing plant. It is somewhat difficult to find generic models specifically developed to evaluate SMO's applicable to manufacturing plants in the literature. However, there are a number of studies done with respect to the sustainability options at the product design stage [10, 11]. Their main focus was to define a product sustainability index by considering sustainability options in three different bottom lines of sustainability; economics, social and environmental aspects. However, when local manufacturing industry is concerned, most organizations do not have their own systematic product design and development process, and some are dependent on the designs given from foreign business partners. Therefore, even though the model proposed in [10] is comprehensive, we cannot use it straightaway for our own evaluation of plants. Hence, the plant specific SM generic model was developed aligning with the triple bottom lines to identify sustainability options in environmental, social and economical aspects. The plant related factors were categorized based on the total life cycle of the product. This includes, supply chain related aspects, product focus issues, built environment of the plant and manufacturing process related aspects.

The motivational factors for implementing SMO's and barriers to implement SMO's were identified by tracing against the generic model with existing plant manufacturing practices. The main motivators and barriers for implementation of SMO's were identified first, and later, appropriate course/reason behind it was done against each relevant SMO of the respective plant. Manufacturing plants selected for evaluation included diverse manufacturing sectors with different scales of economies, ownership, product and market category etc.

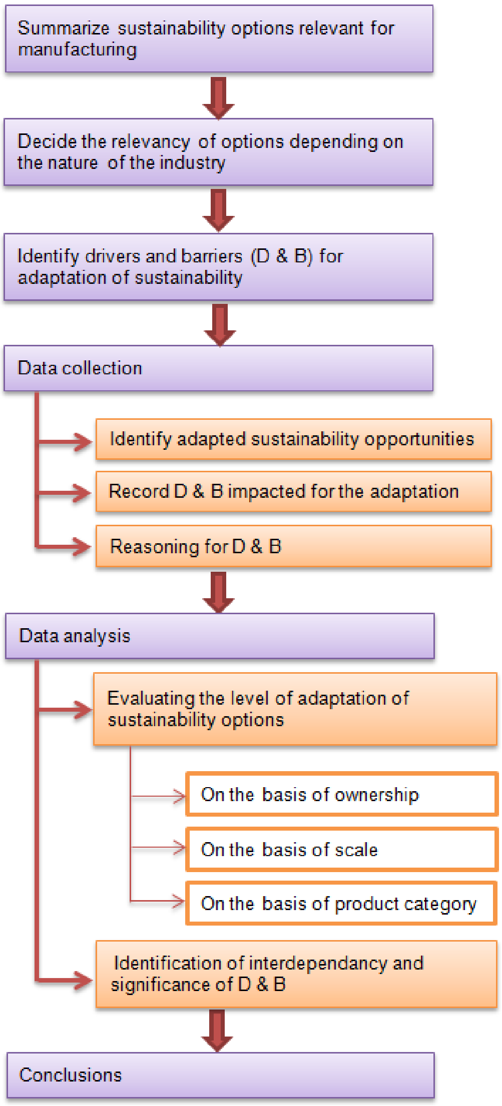


Figure 1: Methodology.

The information was gathered with consultation of Manufacturing or Plant engineers who are qualified graduates in Engineering (Production or Mechanical & Manufacturing specializations) to maintain the homogeneity of the awareness of SMO's and to get expertise feedback from the industries towards this research. The overall frequency of occurrences of different type of motivating factors and de-motivating barriers were counted against each SMO. Based on the analysis of the gathered information, cyclic reasoning models behind all motivating and de-motivating factors were developed for future policymaking purposes towards end of the research. The schematic model of the different phases of the research is given in Figure 1 and the generic SMO model is given in Table 1.

Table 1: Generic model for manufacturing plant sustainability options.

Sustainability Focus		Industry Focus: Supply Chain	Product	Built Environment	Process
	Environmental	Raw material extraction method	Eco design	Rain water harvesting	Substitution with green energy
		Supplier compliance towards green material	LCA analysis	Blue, green water saving	Water efficiency
			Green reporting schemes	Substitution with green energy	Resource efficiency
		Transportation related emissions		HVAC optimization	Adaptation of technologies free of hazardous waste
				Energy saving options	Responsible production
		Inventory/storage reduction			Eco indicators and sustainable aspect calculations
		Chemical leasing			Environmental friendly technology
		Elimination of unwanted packaging			Acquiring of standards (ISO 14001 etc.)
		packing material			Efficiency in material handling
	Economical	Original shape of raw material	Resource efficiency	Selection of the location	Energy Efficient options
		Transportation/Distribution optimization	Usage of recycle material	Centralized facility location	Positive attitudes for energy saving
		Milk run		Day light harnessing (sky light)	Raw material Conversion factor
				Behaviour (switch on off policy)	Process improvement and innovation
					Process visualization
					Product quality standards (ISO 9001)
					Technology Needs Assessment
	Social	Ergonomics raw material extraction, storage loading and transportation	Design for social needs	Indoor air quality	Health and safety
			Reduce packaging	Ergonomics in workstation design	Welfare of the workforce
		Health and safety in raw material extraction and transportation		Health and safety in work	Ergonomics in Process design

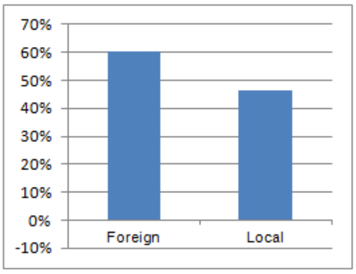
3 CASE STUDY AND RESULTS

A case study was done in order to investigate the current situation of local manufacturing sector in Sri Lanka. Of many manufacturing plants, a sample was selected to carry out the survey by considering the nature of products, market segment, ownership etc. Later, based on the generic SMO guideline shown in Figure 2, each of the selected plant's SMO's were evaluated by interviewing the engineer/s overall plant maintenance and manufacturing operations to check the level of implementation and motivation behind it and vice versa. There were multiple number of reasons behind one SMO in some situations when completing the information gathering. The overall motivational factors and barriers for SMO were analyzed for main and sub issues.

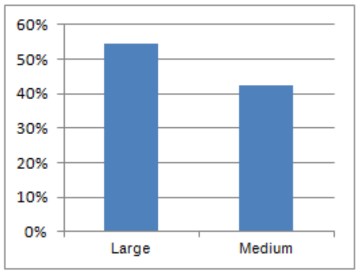
Based on the analysis, level of adaptation of SMO's with respect to previously stated categories are shown in Figure 2. The summarized version of motivational factors and barriers for implementing SMOs of all selected plants are given in Figure 3.

Based on the results and the analysis, it is evident that, when implementing SMOs, majority of manufacturing plants owned by foreigners have adapted about 60 % while the manufacturing plants owned by locals have implemented about 45 % of options available in the generic SMO shown in Table 1. Further, large scale manufacturing plants have implemented SMOs than their medium scale counterparts and respective percentages are 53 % and 42% respectively. When the nature of manufacturing plants are concerned, FMCG sector have adapted majority of SMOs when compared to heavy and assembly sector and apparel sector. FMCG has scored 62% while its closest contender, the apparel sector, has scored 54 % and heavy and assembly sector scored only 41%.

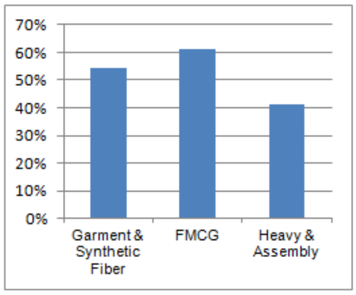
When variations of SMO implementation are concerned, it is evident that awareness towards SM plays a pivotal role. Many developed countries or newly industrialized countries are currently very much aware of SM and the advantages of moving towards that direction. Therefore, they have been self motivated to implement some SMOs. Further, it can be seen that majority of large scale manufacturing organizations too are successful in implementing SMO than their counterparts since they have more exposure to foreign markets and may afford to spend money for foreign consultancy etc. Conversely, locals own most of the medium scale manufacturing organizations and mostly with single ownership category. Majority of them have been developed over the years to cater to the local market and level of awareness of the modern manufacturing related concepts are less.



(A)

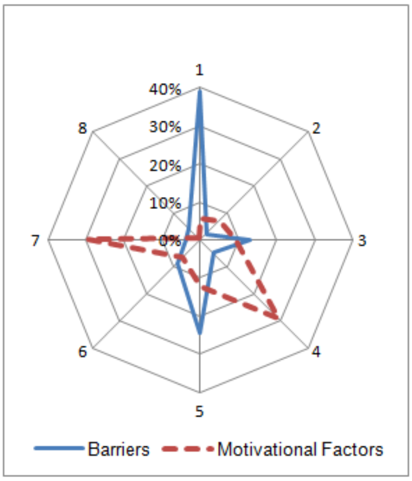


(B)



(C)

Figure 2: Cluster-wise (A-Ownership, B-Scale, C-Manufacturing sector) SMO adaptation in Sri Lankan manufacturing sector.



Main categories of Barriers

1. Lack of awareness sustainability concepts
2. No tax benefit or other rewards from government
3. Lack of awareness programs conducted in locally
4. Lack of awareness of local customers in green products
5. Negative attitudes towards sustainability concepts
6. Less support from the employees
7. Lack of funds for green projects
8. Difficulty for operation and maintenance

Motivational Factors

1. Pressure from market
2. Potential to use as a marketing tool
3. Government promotions and regulations
4. Awareness of the top management
5. Limitations in existing process improvement techniques
6. Success stories of SM in other organizations
7. Economical benefits
8. Availability of funds for green projects

Figure 3: Percentage representation of motivational factors and barriers for implementing SMOs

The main reason behind FMCG's success in adapting SMOs is partially due to the stringent regulations they are subjected to. In addition, a fair share of these companies includes multinational companies. With all these findings, it can be easy to justify the variations shown in the spider diagrams shown in Figure 3; since there are number of loosely coupled relationships that can be seen with respect to the clustering based analysis.

Based on the spider diagrams, the main barrier for SMO implementations is lack of awareness about SMOs or how to recognize those options. This issue accounts for nearly 40% of the cases. This can be even evident from the cluster/category wise comparison done previously as well. The next frequent barrier encountered in the research is the negative attitudes towards SMOs. This issue again inter-links with previous statements. Very lower percentage was due to lack of tax benefits, lack of awareness of local customers on green products and difficulty to operate and maintenance. However, the second largest barrier for SMO implementation is due to the negative attitudes towards sustainability.

When considering the drivers behind SMO adaptation, 40% each were scored by two factors; awareness and commitments of top management and for economical benefits. The least percentages were scored for availability of funds for green projects, success stories on SMOs, government regulations etc. None of the plants highlighted that lack of funding for green initiatives. However, it is difficult to find any strong relationship between barriers and motivational factors shown in Figure 3. Therefore, it can be seen that one motivational factor or barrier leads to one or more factors in this study. Hence, these variations can be shown with a loosely connected relationship chart which is given in Figure 4.

From the spider diagram shown in Figure 3, it is very clear that one barrier leads to many subsequent barriers. For example, lack of awareness on SMOs leads to four other issues and it is dependent on lack of knowledge on building awareness within society. Further, since there are no stringent policies to motivate manufacturers to adopt SMOs, they are not willing to implement SMOs. Due to that, it is difficult to see any success stories, which are available locally, and due to lack of awareness about these concepts within policy making level, even financial sector does not provide any loan schemes etc. to implement such options.

4 DISCUSSION

It is event from the above studies that there are inter dependent issues to both motivate and de-motivate the implementation of SMOs in local manufacturing sector. In order to overcome the barriers currently available in local manufacturing sector, a generic model can be designed based on the findings of previously explained analysis. The foundation of the model should be the awareness on SMOs, which is a must even for governmental officials, policy makers etc. so that they will find it easy to communicate. Once the foundation is laid, an action group should be formulated. This group should consist of academics and researchers who act as bridges to transfer knowledge from research and academic domains to industries. This group should include high-ranking governmental officials from different ministries such as ministry of industries, economic development, environment, power and energy, labour etc. When there is a new project to set up a manufacturing plant, it is necessary to make it mandatory to get necessary approval from above committee,

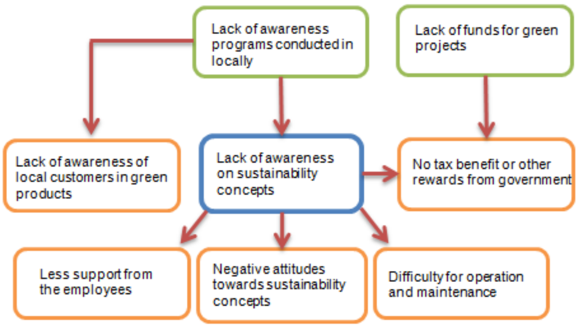


Figure 4: Interdependency of barriers for SMO implementation

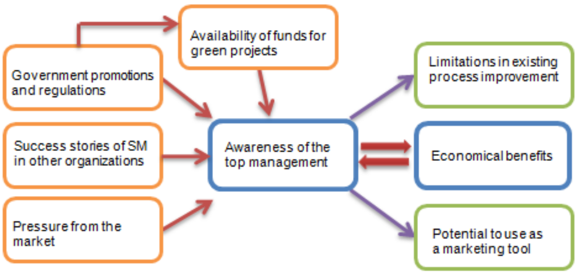


Figure 5: Interdependency of motivational factors for SMO implementation

which will look in to the implementation of SMO and thereby advise investors to adhere to their guidelines. Further, there should be a close relationship between the steering committee and financial organizations of the country, so that necessary funding can be facilitated for SMO implementations after viability of the project is studied. In addition to the interference with new manufacturing plant commissioning, this steering committee can even extend their involvement to assist existing manufacturing plants to convert their practices in line with SM. This can be assisted if the local universities are empowered with necessary human resources, especially facilitating adequate training facilities to the current academics. It is not adequate to provide assistance to implement SMOs, but a frequent monitoring mechanism is also necessary even after implementation of SMOs. In order to motivate those who practice SMOs in their plants, this committee can come up with an awards scheme based on in-depth study of the SMO already been adapted and key organizations successes can be shared in openly accessible domains so that they can be referred to as success stories. For their own development, the SM steering committee should have links with other global networks to share their experiences and development in this discipline and it is essential to organize awareness programs starting from secondary school levels to CEOs of manufacturing companies. Further, local universities can be provided funding to carry out research to develop this concept locally and to come up with customized approaches to match with local settings, especially social and cultural aspects as well.

5 CONCLUSION

This research benefitted to the knowledge from diverse directions. The generic model developed for plant level SMO, can be used to evaluate any manufacturing plants' sustainability options. In addition, this can be used to recognize indirectly the motivational and barriers with respect to SMO. The reasons behind motivational and barriers can be used to recognize where and how to address the core issue behind sustainable implementation and to make society aware of these issues. Therefore, the outcome at this research can be used to develop a policy on SM for Sri Lanka. However, based on the interdependency of different motivational and barriers for implementing SMOs, some inputs can be useful for other developing countries who want to drive their manufacturing sector in the SM direction.

6 REFERENCES

1. http://www.ncpcsrilanka.org/cp_awards.htm
2. http://www.geocycle.lk/?page_id=935
3. http://www.cea.lk/greenawd2012.php
4. http://www.energy.gov.lk/
5. A.K. Kulatunga, P.R. Jayatilaka, E.R. Ekanayake,(2012),"Incorporating Green Building Concepts in Manufacturing Plant Design", ICSBE 2012, Kandy, Sri Lanka
6. A.K. Kulatunga, P.R. Jayatilaka (2012), "Will green building concepts hinder the sustainability in manufacturing sector" ICTAD Journal 2012, Sri Lanka
7. M. Jayawickrama, P. R. Jayatilaka, A. K. Kulatunga (2013), "A Case Study on Level of Adaptation of Sustainability Concepts in Local Manufacturing Sector" 2nd Roundtable on SCP, Colombo Sri Lanka.
8. E.A. R.S Ekanayake, A. K. Kulatunga, K.D.P.R Jayatilaka, (2012), "Incorporating sustainable concepts for Product Design and Development" ICSBE 2012, Kandy, Sri Lanka
9. A.D. Jayal, F. Badurdeen, O.W. Dillon Jr., I.S. Jawahir, Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels, CIRP Journal of Manufacturing Science and Technology, 2 (2010) 144–152
10. A.D. Jayal, F. Badurdeen, O.W. Dillon Jr., I.S. Jawahir, Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels, CIRP Journal of Manufacturing Science and Technology, 2 (2010) 144–152
11. X. Zhang, T. Lu, M. Shuaib, G. Rotella, A. Huang, S.C. Feng, K. Rouch, F. Badurdeen, I. S. Jawahir, A Metrics-based Methodology for Establishing Product Sustainability Index (*ProdSI*) for Manufactured Products, *19th CIRP International Conference on Life Cycle Engineering, Berkeley, 2012*

5.4 Assessment of perspectives and challenges on sustainability in Palestine

H. Arman [1], A. Ramahi[2], F. Abubasha[2], N. Al Othman[2], H. Safadi[2] , M. kmail [2]

[1] Kuwait Institute for Scientific Research, Kuwait, Kuwait

[2] An-Najah National University, Nablus, Palestine

Abstract

Sustainability has rapidly become imperative at a global level. Collaborative work is required to address the global challenges. However, the effort towards sustainability varies between developing and developed countries. Assessing sustainability in Palestine with its unique context can exemplify the awareness and understanding of sustainability in developing countries. The objective of this paper is to assess the awareness of sustainability from different perspectives of government, industry, and academia. The significant of this study is how to promote sustainability in a country with limited resources and special conditions. The primary data was collected through conducting semi-structured and in-depth interviews with CEOs and decision makers of the major stakeholders in government, industry, and academia. In addition, secondary data were used, which included literature review of current practices documented in government and NGOs reports.

Keywords:

Assessment ; Awareness ; Palestine; Sustainability

1 INTRODUCTION

Nowadays, global society is facing scarce water, material, and energy resources. This raised the concerns with regard future generations and their ability to survive in the modern world. As a result, new initiatives and hence concepts were proposed to address the above challenges. Sustainability was one of the main hot topics driving a global trend.

The western industrial revolution increased the environmental effects since manufacturing industry grew very rapidly and therefore more natural resources were depleted and caused larger amount of emissions and pollution. Moreover, the recent new wave of Chinese industrial "revolution" drew the attention of the global community and the necessity to act as soon as possible in order to protect our planet and alleviate the harm.

The concept of sustainable development appeared initially in the early 1980s [1], it then popularized in the publication of the Brundtland report, Our Common Future [2]. The principle of sustainable development has gained general acceptance. This acceptance illustrates the growing awareness of the inherent fragility of the world's ecosystems. Consistent with the UN definition, Brundtland report defined sustainable development as " … meeting the requirements of present generations without undermining the natural resource base, which would compromise the ability of future generations to use these resources" [3].

The contribution of the developing countries perhaps minimal when compared to the industrial ones, yet they are in the same boat. Therefore, cumulative endeavor is required to handle this global issue. Although, the case presented in this paper may not be ideal in this context, it recognizes a sample perspective of how sustainability perceived in situation with special conditions such as Palestine.

2 LITERATURE REVIEW

Government, businesses and academia have expressed a desire to contribute to sustainability by reducing environmental harms, improving social and economic situation for people. However, they are still struggling to identify the best set of alternative solutions. This is due to the lack of collective vision that can embrace a holistic perspective. According to Cowan et al [4], although more than 20 years have passed since the emergence of sustainability, there are still no uniform set of federal rules, regulations, or guidelines to lead the industry in the United States. This example is alarming, since US is considered a major contributor for setting up regulations and long term guidance in various fields and it fails here to address the challenge facing the international community. The view of businesses showed positive attitude towards sustainability in several empirical studies. For example a study conducted by Accenture [5] targeted hundreds of CEOs from companies around the world found that 93% of the companies considered sustainability to be important to their company's future success. Moreover, some companies develop their own sustainability programs because they believe that good environmental practices will increase their profits more effectively than most other business practices [6]. Many firms have experienced that environmentally sustainable practices can create value for a business by increasing revenue and reducing operating costs, so sustainability is now seen as a business opportunity as well [7]. Companies generally agree that sustainability has led to innovation and increased competitiveness by lowering costs and increasing revenues [8].

While many companies recognize the value of a sustainability strategy, most have not yet incorporated sustainability into their overall business strategy [9]. The fact that the concept is comparatively young and complex may have delayed

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

approving logical and efficient framework to manage business operations with alignment of sustainability strategy.

An awareness study was conducted in 2011, for staff and students in the St. Francis Xavier University (StFX) campus to measure the awareness level for environmental sustainability of the campus and region. The dimensions of sustainability included environment, economy, society and cultural sustainability. The survey showed that sustainability issues are important on the personal level for people at StFX [10].

The role of academia and research bodies is important here. A multidisciplinary effort is required from the economists, social scientist, and environmentalists to put together a framework that address the various, sometime conflicting, missions and objectives to address the sustainability challenges.

Very few studies were conducted in Palestine with regard sustainability. However, some data is available on issues related to environment. In spite of this, promising practices is advanced with regard using a viable renewable energy alternative. In July 2011, 66% of households in the Palestinian Territory had solar energy heaters [11]. In 2008, the total imported energy to the Palestinian territories was 43,147 Terra joules, where diesel percentage where 44% (18,920 Terra Joules) of the total imported energy. The electrical energy percentage was 32% (13,913 Terra Joules) of the total imported energy [12]. The drive of such practices was purely financial due to the expensive tariff of electricity. People learned how to utilize the technology in small workshops out of desperation.

This study, at the time of writing this paper, is the first sustainability awareness assessment study in Palestine. It is explorative in its nature, since a generic overview is required at this stage and further systematic examination and assessment should follow based on the initial results.

3 METHODOLOGY

The purpose of this study is to assess the level of awareness of sustainability from different perspectives of government, industry, and academia. To conduct this investigation, mainly a qualitative research approach was used. Moreover, a questionnaire was used as an additional tool to provide further information to the primary approach. Figure 1 depicts the methodology that was followed in this research.

The formulation of the objective of this research was developed after conducting a collaborative project as part of TEMPUS program. Literature review was used to further understand the concept of sustainability and help to design the research method. Qualitative and quantitative approach was used where semi-structured interviews were conducted and a straightforward questionnaire. The interviews targeted three key stakeholders; government, industry, and academia. The participants were selected carefully in order to reflect rigid and considerable view. For example CEOs were interviewed for large firms, University Presidents Assistant for academic affairs, and senior government representatives in the relevant bodies.

The questions of the semi-structured interviews focused on five themes where set of questions would address each theme after asking general questions about sustainability practices. Each interview took approximately 45-60 minutes to complete. The selected themes were water, energy, materials, pollution and environment. These are the major themes and believed the most relevant and urgent in Palestine.

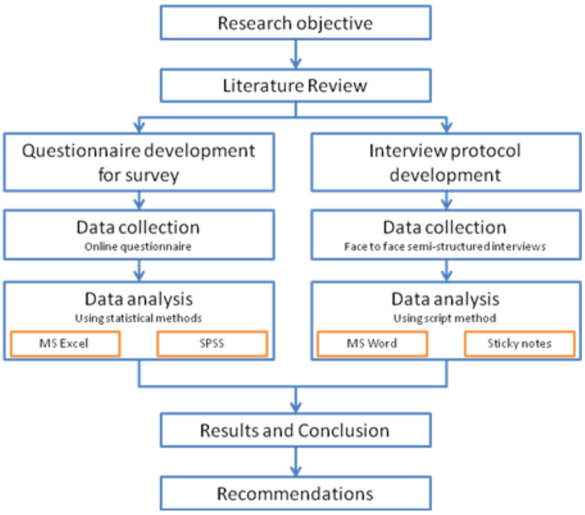


Figure 1: Research Methodology.

A survey was designed to enhance the study by including another side perspective which was represented by a sample of students from An-Najah National University in Nablus, Palestine. The questionnaire was available online for 10 days. The link to the questionnaire was distributed by e-mail and on students' pages on Facebook

The questionnaire took approximately five minutes to complete. The purpose of the first set of questions was to gather general personal information and assess the awareness of sustainability in general. The next set of questions addressed the same five themes followed in the interview (water, energy, materials, pollution and environment). A total of 377 participants completed all questions in the survey from all the faculties in the university.

4 ANALYSIS AND RESULTS: SUSTAINABILITY AWARENESS

4.1 Government

The interviews transcripts were analyzed to examine the common issues perceived for each theme from the three different perspectives. The general view of government was positive towards acting upon sustainability matter and they showed general awareness with this regard in terms of understanding its importance. However, it failed to initiate laws to regulate the various sustainability related activities. Moreover, few awareness activities were organized in the past and very few are planned for this matter. This indicates that lack of awareness in specific areas which means no real actions has been taken to improve the situation and make progress.

The various interviewed bodies in the government showed lack of coordination between them with regard the activities designed to support the effort towards increasing the awareness of sustainability in the community. Moreover, the lack of physical and specialized human resources prevents the governmental authorities to enforce the current outdated regulations.

4.2 Industry

The awareness in the industry showed varied results as some firms had already took actions towards this issue while others seemed to be almost ignorant. Part of this would be an indication of the lack of awareness and the absence of laws that force businesses to be sustainable. In spite of this, the competent firms were only interested in the area where significant savings can be achieved in applying sustainable concepts and would reflect positive financial results. Moreover, the lack of resources encouraged firms to look at more sustainable approaches in their processes as was the case of some manufacturing firms in the south of Palestine where water is very scarce.

4.3 Academia

The third investigated perspective was the role of academic institution and their awareness through looking at the programs and curriculums, research programs, and various related activities such as conferences, workshops and seminars. The results showed that the top universities in the country have already taken some initiatives in collaboration with European universities to develop academic programs in sustainability. However, most of the current programs have very few topics in the courses that cover any of the sustainability topics.

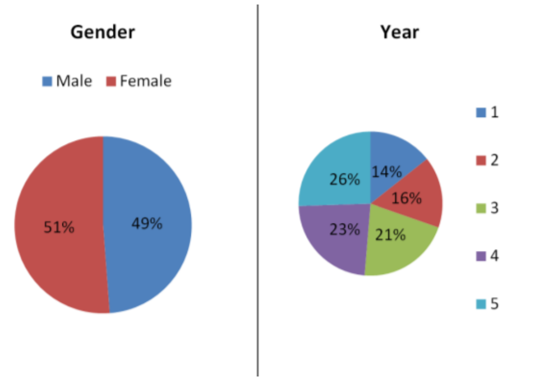


Figure 2:The distribution of the participants in the survey according to gender, faculty, and year of study.

The analysis of the questions related to students practices and observation at the University is summarized in details in Figure 3. The general portrait shows low awareness in most of the issues they were asked to respond except the issue regarding the reuse of some of the consumable products (point 2) which is a practice that may be attributed to the lack of physical resources and its associated costs. The other exception was related to ethical behavior to do with culture (point 7) as people are trying to save money and reuse whatever they can.

Figure 3: Results of each question in the students' survey

An online questionnaire was used to collect university students' views about sustainability in general and of the university role. The distribution of the respondents with regard gender and year of study is shown in Figure 2.

However, all the other issues such as projects, courses, policies, awareness activities in sustainability seem to be lacking and have not been a priority or areas of concern for the decision makers in the universities according to the students' perspective. This support the results obtained from the interview with the academic top management in the universities.

5 CONCLUSIONS

The results of this initial study with regard the sustainability awareness level was not as poor as it was expected considering the very special political conditions of Palestine and being one of the very developed countries. The level of awareness can be qualitatively considered low as the practical activities (i.e. sustainability laws, projects, initiatives, etc) considered very limited when compared to other countries in the region. The sample of the young educated community, represented by the university students, showed passive perceptions towards sustainability and lack of awareness as well. However, the special condition and difficult challenges in Palestine can be a source of innovative sustainability solution to compensate for resource scarcity especially in the situation where advanced technology is not necessarily required. The culture of reuse ideas was a good example. These solutions can be publicized globally where appropriate since normal environment as the case in developed countries may not ignite the same level of creativity in finding new sustainable solutions.

6 REFERENCES

[1] IUCN (1980). World conservation strategy: living resource conservation for sustainable development, UICN/PNUE/WWF, Gland

[2] WCED (1987). Our Common Future: Report of the World Commission on Environment and Development, UN General Assembly, doc. A/42/427

[3] Wiersum, K. F. (1995). 200 years of sustainability in forestry: Lessons from history, Environmental Management, 19(3) pp 321-329

[4] Cowan, D. M., Dopart, P., Ferracini, T., Sahmel, J., Merryman, K., Gaffney, S., Paustenbach. D (2010). A cross-sectional analysis of reported corporate environmental sustainability practices. Regulatory Toxicology and Pharmacology 58 (3) pp 524–538.

[5] Accenture and United Nations Global Compact (2010). A New Era of Sustainability: UN Global Compact—Accenture CEO Study 2010.

[6] Epstein, M., Elkington , J., Leonard, H. (2008). Making Sustainability Work: Best Practices in Managing and Measuring Corporate Social, Environmental, and Economic. Berrett-Koehler Publishers.

[7] Satterfield, M B, Kolb, C E, Peoples, R, Adams, G L, Schuster, D S, Ramsey, H C,

[8] Stechel, E, Wood-Black, F, Garant, R J and Abraham, M A, 2009 (2009). Overcomingnontechnical barriers to the implementation of sustainable solutions in industry. Environmental Science and Technology, 43 (12), pp 4221–4226

[9] Nidumolu, R., Prahalad, C. K., and Rangaswami, M. R. 2009. Why sustainability is now the key driver of innovation. Harvard Business Review 87(9): 57-64

[10] Richard M. & Kashmanian, R. P. (2011). Corporate Environmental Sustainability Strategy. Greenleaf Publishing.

[11] Palestinian Central Bureau of Statistics (PCBS) (2012). Press Release on World Environment Day.

[12] Palestinian Central Bureau of Statistics (PCBS) (2008). Balance of power in the Palestinian Territories.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

5.5 Energy efficiency in production processes – the influence of consumption visualization and staff training

S. Asmus[1], F. Karl[2,3], M. Grassl[3], A. Mohnen[1], G. Reinhart[2,3]

[1] Chair of Corporate Management, Technische Universitaet Muenchen, Germany

[2] Institute for Machine Tools and Industrial Management, Technische Universitaet Muenchen, Germany

[3] Fraunhofer IWU Project Group Resource Efficient Processing Machines, Augsburg, Germany

Abstract

This paper examines the influence of the visualization of consumed compressed air and staff training on the consumption behavior of employees in a real production process. To measure potential changes in consumption behavior a real-effort experiment at the Training Factory for Energy Productivity, a real production setting at *iwb* of TUM, had been designed. Therefore, four groups were defined, each group in a different experimental setting. This experiment is the first one ever conducted in a real-life setting and thus adds valuable results to academia and practitioners. Compared to the group without any information about the amount of consumed compressed air the participants provided with a display showing this information saved on average 7-8%. The group provided with a movie about general measures to save compressed air in production consumed around 24% less compressed air than all other groups of participants. Generally, no significant differences between male and female participants had been found.

Keywords:

Empirical study, employee behavior, energy efficiency, production, sustainable manufacturing

1 INTRODUCTION

Today's manufacturing companies are faced with the need to reduce energy consumption sustainably [1]. Growing energy prices [2] due to the increasing demand for energy are only one reason. Moreover, in companies large energy saving potentials that allow for increasing energy efficiency still exist [3, 4].

In order to sensitize people for energy efficiency and show possibilities to reduce energy consumption the Training Factory for Energy Productivity (Lernfabrik für Energieproduktivität, LEP) was built up at *iwb* (Institute for Machine Tools and Industrial Management, see figure 1) [5].

Figure 1: Training Factory for Energy Productivity.

At LEP a small gearbox is manufactured. Therefore, the shaft is turned, the main gear hardened by heating and quenching and finally the gearbox assembled. To display the manufacturing process machines of different ages, automatic as well as manual processes and different forms of energy (steam, electricity, thermal energy and compressed air) are used.

During a sensitization training at LEP participants from all hierarchical levels learn and practically apply a methodological approach that can directly be utilized in real production environments, the Energy Value Stream (EVS) [6]. EVS mainly consists of two phases: the analysis and the design phase (see figure 2).

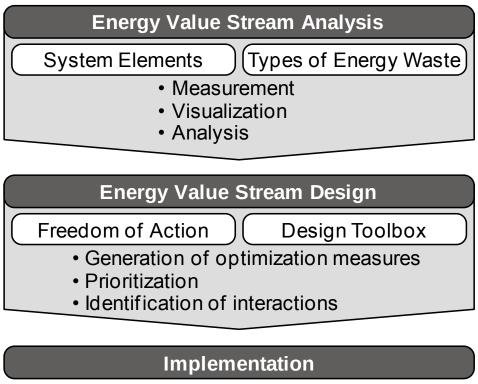


Figure 2: Energy Value Stream (EVS).

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

EVS was deduced from the methodology value stream mapping from Lean Management [7]. During the analysis phase energy waste is identified by measuring energy consumption in a defined area, visualizing the values and applying various analysis methods. Thereby, the three system elements (technology & system, organization & management, human & behavior [8]) and different types of energy waste (overproduction, dead time, transport, inventory, rejections, movements, unused potential of employees) have to be considered. The design phase aims at limiting energy waste. For this purpose the freedoms of action have to be defined and optimization measures generated by applying a design toolbox. Then measures are prioritized regarding their complexity and cost effectiveness. After choosing the right measures, they have to be implemented.

When optimizing production technological systems the three already mentioned system elements need to be considered. Since numerous works in the fields of the first two elements were already carried out [9] this article focuses on human & behavior. Furthermore, workers in production have due to their behavior a large influence on energy consumption. Therefore, a study was carried out to analyze their influence. For this purpose a process step at LEP was chosen where workers' behavior affects energy consumption. Hence, the final assembly station was picked. Here, the gear box is screwed pneumatically by 6 bolts. Another reason for choosing this process was the use of compressed air, as the economical application of compressed air is crucial due to its poor degree of efficiency. The worker can influence the consumption of compressed air by setting the pressure at the workplace.

The findings of the study will be presented in the following chapters. It was conducted in an interdisciplinary team consisting of engineers and behavioral economists.

2 STATE OF THE ART

Even though the public discussion about resource efficiency, environmental issues and climate protection increased tremendously over the past years [10] only a few studies on energy efficient measures in the work-place context have been conducted so far [11]. One of the few studies in that field is the work of Siero et. al. about the influence of goal-setting, feedback and education on employees' behaviour [12]. They figured out that among other things creating awareness for the topic of energy efficiency as well as goal-directed education and feedback lead to significant behaviour changes of the workforce resulting in less energy-wasting.

In order to enhance the available findings on how to increase resource efficiency in the work place established concepts from the field of behavioural economics should be applied [13, 14]. Therefore, this study will put strong emphasize on the feedback mechanism consumption visualization and staff training also as potential measures to increase energy efficiency in production processes.

3 SETUP OF THE STUDY

The experiment took place at LEP in November and December 2012. In total 160 students took part in the study and were randomly distributed to the four different conditions of the experiment. The experiment took between 45 and 60 minutes for each participant and they were remunerated with a fixed payment of 8 euros. In each experimental group consisting of 40 students 13 had been female and the other 27 male. Therefore, an equal gender distribution over the groups is guaranteed. The general experimental setting can be seen in figure 3.

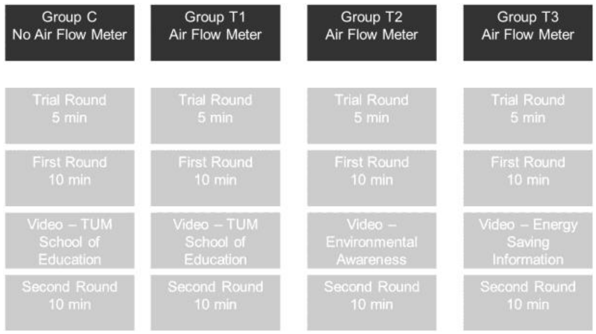


Figure 3: Experimental setting.

Before the experiment started participants were introduced to the work station by a power point presentation and a video to ensure a standardized procedure for every participant. Following, all participants got a five minutes lasting trial round to get familiar with the work place setting and the task. After a short break with additional information people started with the first round which took 10 minutes. Depending on the group the students belonged to a certain movie was shown to them which had duration of around five minutes. Group C and T1 saw a movie about a new faculty at Technische Universitaet Muenchen (TUM), the TUM School of Education. The movie had no relation to the task, the environment or energy saving information. Group T2 got a movie showing nature scenes to address the environmental awareness of the participants. To group T3 a movie was shown which gave particular information on how to reduce consumption of compressed air in production. After the movie participants did execute the second round of the experiment for ten minutes. The last step of the procedure was a questionnaire which had to be filled in by all participants.

As it can be seen in figure 3 groups T1, T2 and T3 had an air flow meter next to them on the work station during the whole duration of the experiment. Therefore, they were able to get continuous information about their cumulated consumption of compressed air.

After each of the three rounds the experimenter counted the finished and unfinished gear boxes the participant performed. This number was after the experiment compared to the used amount of compressed air by each round to calculate the exact number of litres of compressed air per screwed bolt (l/bolt).

4 RESULTS

4.1 Differences between experiment rounds and treatment

First of all the influence of visualizing consumption of compressed air on participants' behavior is shown. To isolate the effect of the display on the consumption only the results of the trial round and the first round are taken into consideration since besides the display's appearance for groups T1 – T3 and non-appearance for the control group everything is equal over all four groups in these two rounds. As it can be seen in table 1 where the results are ordered by the experiment sequence in the trial round group C uses on average 10.76 l/bolt and the treatment groups between 9.87 and 10.18 l/bolt. This results in a saving between 5.4% and 8.3% per group and 7.2% in average over all three groups in the trial round only due to the display. Having a closer look on the first round the savings related to the visualization of the energy consumption are between 6.6% and 9.7% per group and on average 7.6% over the three groups with a display compared to the control group.

Round	Group	N	Mean (l/bolt)	SD (l/bolt)
T	C	40	10.76	0.85
	T1	40	10.18	1.15
	T2	40	9.87	1.04
	T3	40	9.90	0.92
1	C	40	10.68	0.67
	T1	40	9.98	1.19
	T2	40	9.64	1.25
	T3	40	9.98	1.09
2	C	40	10.72	0.72
	T1	40	10.08	1.39
	T2	40	9.60	1.38
	T3	40	7.54	1.41

Table 1: Energy consumption within the three rounds.

Table 2 illustrates the mean consumption of compressed air ordered by group. Interestingly no noteworthy learning effects in terms of energy efficiency can be seen when comparing the mean consumption per bolt between the periods for every single group. This is an important finding because occurring differences between the groups and periods will be based on the different treatments and not on potential learning effects regarding the usage of compressed air.

While the consumption of the groups C, T1 and T2 remains relatively constant over time the consumption of group T3 drops from round one to round two by 24.4%. This implies two major findings. First of all, the purely confrontation of the participants with a video showing nature sceneries to build environmental awareness as done with group T2 has no impact on the energy consumption behavior of people. Only staff training on how to save energy while doing a certain task, not related to any environmental issue, leads to significantly decreasing energy consumption as it can be seen in the results of group T3. As expected the movie which was unrelated to the whole experiment and presented to the control group and T1 had no influence on participants' behavior.

Group	Round	N	Mean (l/bolt)	SD (l/bolt)
C	T	40	10.76	0.85
	1	40	10.68	0.67
	2	40	10.72	0.72
T1	T	40	10.18	1.15
	1	40	9.98	1.19
	2	40	10.08	1.39
T2	T	40	9.87	1.04
	1	40	9.64	1.25
	2	40	9.60	1.38
T3	T	40	9.90	0.92
	1	40	9.98	1.09
	2	40	7.54	1.41
Total	T	160	10.18	1.05
	1	160	10.07	1.13
	2	160	9.48	1.73

Table 2: Energy consumption within the four groups.

To get a deeper understanding of the discussed findings the boxplot in figure 4 visualizes the results, differentiating between the three rounds of the experiment and additionally between the four groups. What becomes very obvious here is that the energy consumption of different people varies considerably. While the 25th percentile (lower quartile), the 75th percentile (upper quartile) and especially the medians are rather similar over time for groups C, T1 and T2 the consumption of group T3 in the second round is strongly affected by the additional information on energy saving and therefore drastically lower as discussed above.

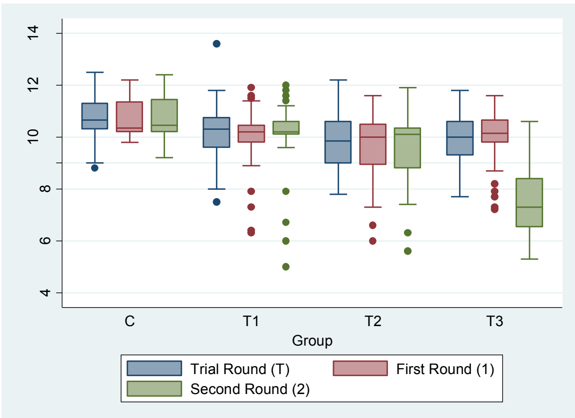


Figure 4: Boxplot of the consumption distribution.

In order to figure out if the consumption differences between the four conditions in that experiment are statistically significant the results of a Bonferroni test for each of the three rounds was executed. Based on the number of experimental groups a multiple comparison of the means between all groups is done in table 3. In this table the means of the consumption are compared group by group and the differences are shown with a positive or negative sign in front of the mean value difference. In the trial round group T1 which had the visualization on the consumption uses on average -0.575 l/bolt less than group C who had no feedback on the energy usage. Additionally to the mean savings per round measured in l/bolt the related significance levels are shown in the table always below the number of the mean savings. In this example p=0.065 and with p>0.05 not significant on the 5% level. Therefore, the difference in this comparison is not statistically significant.

Trial Round

Row Mean – Column Mean	C	T1	T2
T1			
deviation	-0.575		
p-value	0.065		
T2			
deviation	-0.8875	-0.3125	
p-value	0.001	0.978	
T3			
deviation	-0.8525	-0.2775	0.035
p-value	0.001	1.000	1.000

First Round

Row Mean – Column Mean	C	T1	T2
T1			
deviation	-0.695		
p-value	0.026		
T2			
deviation	-1.04	-0.345	
p-value	0.000	0.917	
T3			
deviation	-0.6975	-0.0025	0.3425
p-value	0.025	1.000	0.935

Second Round

Row Mean – Column Mean	C	T1	T2
T1			
deviation	-0.635		
p-value	0.155		
T2			
deviation	-1.1175	-0.4825	
p-value	0.001	0.536	
T3			
deviation	-3.18	-2.545	-2.0625
p-value	0.000	0.000	0.000

Table 3: Comparison of the mean consumption (in [l/bolt]).

By taking a closer look on the results of the second round it can be seen that the mean consumption of group T3 is 3.18 l/bolt lower compared to the control group. Below that value the p-value is given. The related p-value to the value 3.18 l/bolt is 0.000, and with $p < 0.001$ highly significant. For the second round of the experiment all p-values of T3 compared to the other groups are 0.000 and therefore highly significant on the 1% level. This supports the findings of the descriptive comparison of the means for the second round in table 1 and 2 as seen above.

4.2 Gender differences

Because of the fact that the number of female participants in the experiment is equally distributed over the four groups the consumption between male and female students can easily be compared. The results in figure 5 show that the consumption levels of both genders are nearly at the same level comparing every single round and every single condition separately. Female participants on average over all groups consumed 9.43 l/bolt and therefore a little less than their male counterparts who consumed on average over all groups 9.51 l/bolt.

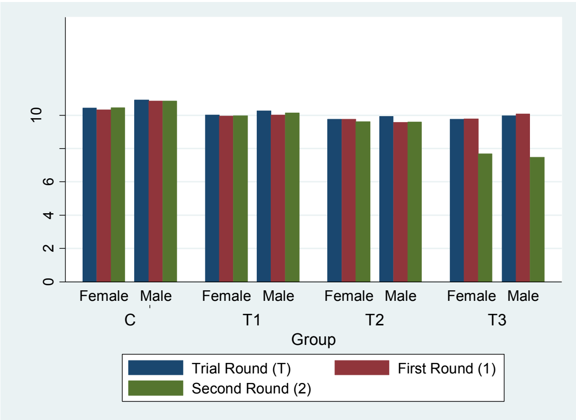


Figure 5: Consumption comparison by gender.

4.3 Goal changing behavior

In the questionnaire after the experiment students were asked to name their major goal for each of the two rounds. They had to choose between either a) produce high quantities (Quan), b) avoid mistakes (Qual) or c) save energy (Energy). Table 4 shows separately for round one and round two the answers of the participants, differentiating between the four experimental groups. The numbers in brackets show the percentages of students per group which chose a particular goal.

For groups C, T1 and T2 it can be seen that the number of students who named as their major goal to produce high quantities rose from round one to round two tremendously. Over the three groups the percentage increased from 33.9% to 73.5%. In comparison the number of students who were trying to avoid mistakes or save energy decreased strongly in these groups between the rounds.

Round	Group	N	Quan	Qual	Energy
1	C	40	16 40%	24 60%	0 0%
	T1	40	13 33%	17 42%	10 25%
	T2	38	11 29%	20 53%	7 18%
	T3	39	23 59%	16 41%	0 0%
	Total	157	63 40%	77 49%	17 11%
2	C	40	34 85%	6 15%	0 0%
	T1	40	27 68%	8 20%	5 12%
	T2	37	25 68%	6 16%	6 16%
	T3	39	15 38%	3 8%	21 54%
	Total	156	101 65%	23 15%	32 20%

Table 4: Change of participants' main goal between rounds.

In contrast, participants of group T3 changed their behavior in a different direction. More than 50% of them were looking mainly on reducing energy consumption in round two, while none of them called energy savings the main goal in the first round.

Based on these results it becomes obvious that in case people get more confident and familiar with a certain task they tend to focus more on producing high numbers while taking less the quality and the energy consumption into account. In contrast to that people who get a certain external impulse on how to change behavior related to energy efficiency, these people do focus more on that goal dimension. These findings are supported by the comparison of the increase of inserted bolts. While all groups completed on average 72 – 74 bolts in the first round the groups C, T1 and T2 realized 79 – 82 bolts in the second round while T3 grew only slightly from 74 to 75 bolts in the second round.

4.4 Results summary

To sum up the most important findings of the study are:

- Energy can be saved only by visualizing the consumption.
- General sensitization regarding environmental awareness has no effect on behavior.
- Workers have to be sensitized and trained on the specific topic to behave in a more energy efficient way.
- Between females and males no significant behavior differences related to energy saving behavior exist.
- Even without financial incentives people do change behavior based on additional information.

5 CONCLUSION AND OUTLOOK

This paper presented a study to analyze the influence of energy consumption visualization and task-related information on workers' behavior. To conduct this experiment a work station to assemble gear boxes with a pneumatic screw driver was chosen and the behavior of 160 participants analyzed. Four different groups consisting of 40 participants each were defined and separated in different treatments. Generally, the strength of the influence of workers' behavior on the energy usage in a certain production step became obvious. The most important findings are that simply showing the consumption of compressed air during the production process to the worker reduces the consumption by around 7%. By giving additional task-related training with a focus on saving energy participants reduced the compressed air consumption by additional 24%. There haven't been found any significant differences between the results of female and male participants.

Future research should first replicate the scenario in a completely real production setting in industry to validate the results of that experiment. Furthermore, other related topics should be tested in the LEP-setting to gain further insights on human behavior and the reaction on consumption visualization, additional task-related information or other related topics to enable and foster energy efficient behavior.

To ensure that the experimental setting is as close as possible to a real production environment the three main goal dimensions in production settings namely energy efficiency (in broader terms material efficiency), product quality, and produced quantity have to be taken into account jointly.

6 ACKNOWLEDGMENTS

We extend our sincere thanks to the Free State of Bavaria for funding the project Green Factory Bavaria in the framework of the future initiative "Aufbruch Bayern".

7 REFERENCES

[1] Abele, E., Reinhart, G., 2011, Zukunft der Produktion, Hanser, München.

[2] Kleiner M., Tekkaya A. E., Becker D., Pietzka, D., Schikorra, M., 2009, Combination of curved profile extrusion and composite extrusion for increased light-weight properties, Production Engineering - Research and Development, 3:63-68.

[3] McKinsey (ed.), 2009, Energy: A key to competitive advantage, Frankfurt.

[4] Neugebauer, R., Westkämper, E., Klocke, F., Kuhn, A., Schenk, M., Michaelis, A., Spath, D., Weidner, E., 2008, Untersuchung zur Energieeffizienz in der Produktion, Fraunhofer Gesellschaft, München.

[5] Reinhart, G., Karl, F., 2011, Live Experience of Energy Productivity – The Training Factory at Technische Universitaet Muenchen (TUM), 1st Conference on Learning Factories, Darmstadt.

[6] Reinhart, G., Karl, F., Krebs, P., Maier, T., Niehues, K., Niehues, M., Reinhardt, S., 2011, Energiewert-stromdesign, wt Werktstattechnik online, 4/101:253-260.

[7] Rother, M., Shook, J., Womack, J.P., 2000, Training to See, Lean Enterprise Institute, Brookline.

[8] Bullinger, H.-J., Spath, D., Warnecke, H.-J., Westkämper, E., 2009, Handbuch Unternehmens-organisation: Strategien, Planung, Umsetzung, Springer, Berlin.

[9] Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012, Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals – Manufacturing Technology, 61:587-609.

[10] Belz, F.-M., Peattie, K., 2009, Sustainability Marketing: A Global Perspective, John Wiley & Sons, Chichester.

[11] Carrico, A.R., Riemer, M., 2011, Motivating Energy Conservation in the workplace: An Evaluation of the Use of Group-Level Feedback and Peer Education, Journal of Environmental Psychology, 1/31:1-13.

[12] Siero, F.W., Bakker, A.B., Dekker, G.B., van den Burg, M.T.C., 1996, Changing Organizational Energy Consumption Behavior Through Comparative Feedback, Journal of Environmental Psychology, 3/16:235-246.

[13] Tversky, A., Kahneman, D., 1973, Judgement under Uncertainty: Heuristics and Biases, Science, September /185:1124-1131.

[14] Tversky, A., Kahneman, D., 1981, The Framing of Decisions and the Psychology of Choice, Science, January /211:453-458.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

5.6 Proposed framework for End-Of-Life vehicle recycling system implementation in Malaysia

Muhammad Azmi [1], Muhamad Zameri Mat Saman [1], Safian Sharif [1],
Norhayati Zakuan [2], Salwa Mahmood [1]
[1]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia
[2]Faculty of Management and Human Resource Development, Universiti Teknologi Malaysia,
81310 Johor Bahru, Malaysia

Abstract

Normally in Malaysia, vehicles are being used extensively regardless of its age or condition. This situation is not only in rural areas but exists in major cities. Vehicle manufacturers expected their vehicles to last in 15 years, hence vehicles exceeding this limit are considered as End-of-Life Vehicle (ELV). The extensive usage of ELV may lead to vehicle failure which threatens the safety of its user as well as other road users. ELV usage also contributes to environmental pollution. In order to overcome this, a framework for ELV management needs to be developed. Prior to that, a survey was done to study the current practice being applied in Malaysia. This paper also study the existing framework applied by other countries as adaptation for Malaysian ELV recycling implementation framework. This framework is expected to assist the government in drafting new ELV related policies.

Keywords:
ELV; Framework; Vehicle Recycling; Vehicle Recovery

1 INTRODUCTION

Total number of vehicle in Malaysia had reached a cumulative amount of 21.25 million vehicles at the end of year 2010 with an average of 12% increase of vehicle registration each year over the period of 5 years. If the estimation was to be continued, Malaysia will have as much as 31 million vehicles in the year 2020. As the automotive industry develops, its impact to the environment also increases. Thus, a proper solution of managing waste is needed to sustain the environment and reduce human impact towards nature.

The disposal of End-of-Life Vehicles (ELVs) is of high concern to achieve sustainable development in any country. Maximum recovery and recycling needed to be achieved to reduce waste discharge and to change the image of the automobile industry through environmentally sound management. Lately, ELV management has been launched extensively in developed nations to establish an appropriate recycling system using the best available technologies. For European Union, the End-of-Life Vehicle Directive has passed laws to the member countries to reuse and recover 85% by weight of the average vehicle in year 2006 and this percentage is expected to increase to 95% by year 2015.

After the establishment of National Car Project in 1985, the automotive industry in Malaysia has grown tremendously. However, Malaysia has not dealt with the environmental impact of the automotive industry sustainable development. To date, directive or legislation on End-of-Life Vehicles for the automotive industry has not been established even though an attempt was done in 2009 but later withdrawn due to fierce rejection by public. It was known later that the legislation was introduced without proper research and has too many loose ends. As a result, Malaysia have a very low vehicle scrap rate and relatively high vehicle age. Several countries in Asia have started the effort on reversing the problem of ELV accumulation or overpopulation. This campaign was triggered by the European Union (EU) with an ELV law in September 2000 and had since lead Japan and Korea to follow suit with tailored version of ELV Law. These countries recognized that a distinct ELV law is necessary within the framework of the extended producer responsibility (EPR) system. Japan, Canada and Taiwan had reported success in controlling the number of ELV off the road.

Due to the success of countries implementing ELV law, a SWOT analysis on the respective framework had also been done. The results from this analysis will be used to model a new framework ideal to Malaysian current and future condition.

2 LITERATURE REVIEW AND METHODOLOGY

Waste treatment has become an important issue and a serious concern to the environmental conscious society. Concerns about reducing waste during the generation process have been emphasized as the first priority before further treatment. Waste form ELVs is also one of the recently emerging waste streams. This had led to a need to achieve maximum recovery level with less amount of waste discharge. Among efforts to reduce the amount of ELV waste is by extending the lifetime of a vehicle, lowering exhaust gas emissions, and changing materials for easier recycling or recovery in the industry [1]. Waste treatment is required as environmental management practices and to enhance the image of automobile industries. Malaysian National car maker PROTON in response with recent EU legislations, the Directive 2000/53/EC European Commission had to change approach in designing and manufacturing of its product [2].

After 52 years of independence, the Malaysian government had introduced the National Automotive Policy to boost the countries participation in the automotive industry with aiming to be the hub of regional automotive industry. However, the National Automotive Policy has not dealt with the environmental impact of the automotive industry development. To date, directives or legislation on End-of-Life Vehicles for the automotive industry have not been established exclusively. In the EU countries, the directive is seen as a pushing factor for the establishment of an environmentally conscious automotive industry [3]. It is noted that in National Automotive Policy, ELV related policy will be introduced gradually with first implementation which was a mandatory annual inspection of vehicles with 15 years of age or older for road tax renewal. This policy however is later withdrawn.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

End-of-life vehicle recycling in Malaysia however is being done by 5000 small companies bound under associations such as Malaysia Automotive Recyclers Association (MAARA) and working without a standard working practice [4]. The business was run in similar way as regular car workshops thus a proper regulation should be in place to improve and control the current practice in recycling ELV. Vehicles usually imported from developed nations such as Japan and European countries to be dismantled and sourced for parts which are still usable and in working conditions. Unusable components then are sent to the smelter plants to be melted for recycling purpose or sent to the junkyard. Moreover, recycling resources such as engine oil and coolant of air condition units such as chlorofluorocarbon (CFC) is not appropriately handled due to lack of equipment, information and skills. Consequently global warming and soil pollution problems are accelerated. Currently, there is no exact figure available to describe the number of ELVs that have been recovered in Malaysia.

The ELVs directive is needed to boost the number of reuse and remanufacturing vehicles parts–components, increase the number of recycled materials, regulate the use of hazard or toxic materials, and facilitate OEMs in ELVs-recovery programs. As more vehicle manufacturers starting to flock into Malaysia, a regulation is developing sustainable and environmental conscious local manufacturers is seems fairly justified.

The first step for this study was to gain the current practice of ELV Recycling system in Malaysia. For this step, the author chooses to use Qualitative Data Collection and complemented with Quantitative data collection for framework validation later. Interviews seems to be the best method compared to questionnaire because the current situation is unknown or yet to be documented.

The first round of data collection was done using Qualitative data Collection techniques. The chosen methods are interviews and direct observation. A total of 8 companies had been interviewed. 2 of the interviews were done via structured interview while the rest was using participant interview techniques. Each interview only last between 20 minutes to 1 hour. Participant for this interviews are; 5 ELV Recycling companies, 2 workshops and 1 used tire reseller. The best input was provided by the ELV recycling companies.

For the interview questions, a set of open ended questions are being asked. Such questions includes details of how dismantling activities is being done, how the safety of the activities being monitored, how parts reliability and safety are being tested. Second main criteria being investigate is the shredding process while waste which being transferred to landfill is the third important criteria. The question set also includes the environmental related questions such as the awareness of the company on environmental law and legislation. Later, a questionnaire consists of a Current ELV Recycling System to respondents for validation as shown in Figure 1.

The second part which is the proposed Framework, the analysis of Strength-Weakness-Opportunity-Threat was done on several countries ELV management Framework namely Japan, Canada, Taiwan, China, and Korea which was obtained from related journals and publications. Results will then be used to model this proposed framework.

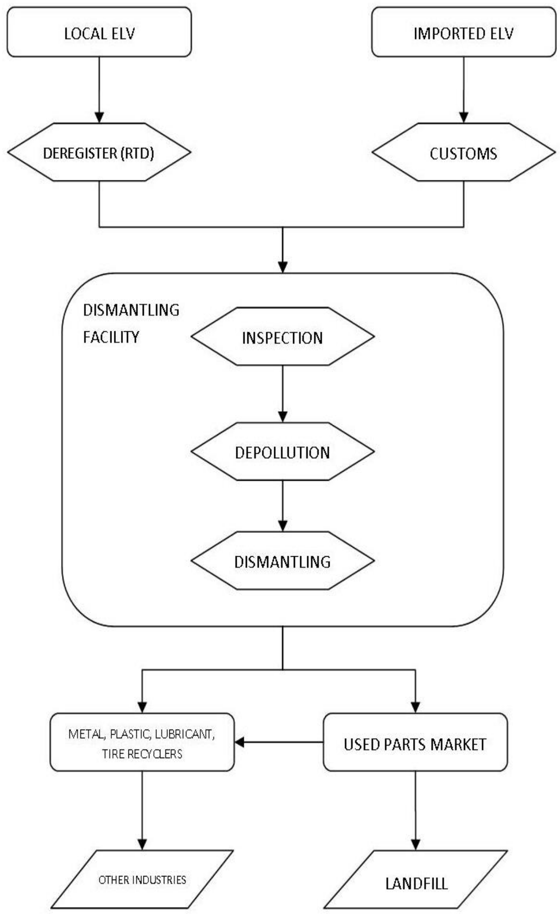


Figure 1: Current ELV recycling system in Malaysia

3 CURRENT SITUATION

3.1 Legislation Requirement

The first row of Table 1 addresses the legislation by seven countries; Taiwan, China, Korea, Japan, Canada, Singapore, and Malaysia regarding ELV recycling. All mentioned countries have enacted their own version of regulation to enforce ELV recycling except for Canada and Malaysia.

Automotive Recyclers of Canada (ARC) estimates that 600,000 vehicles leave the road annually in Ontario. This is half the total estimation of 1.2 million vehicles for Canada. Approximately 1.2 million vehicles are taken off the road annually in Canada. This creates more than 150,000 tons of vehicle waste which is introduced into landfills in Ontario alone. This volume includes contaminated materials which in time will pollute the soil. Despite his huge numbers, law on ELV is still not being introduced by the Canadian government.

In term of jurisdiction and mandatory ELV recycling (also called vehicle retirement), each province in Canada has their own regulations initiative but not in federal government level.

Table 1: Comparison of ELV management system between countries

	Taiwan [5]	China [6]	Korea [7]	Japan [8]	Canada [9]	Singapore [10]	Malaysia
Government Involvement / Act :	Waste Disposal Act	Statute 307 Law on ELV	The Act for Resource Recycling of Electrical/ Electronic Products and Automobiles	End-of-Life Vehicle Recycling Law	None (Voluntary)	Vehicle Quota System	No Law
Manufacturer Involvement:	None	None	None	Take back CFC, Airbag unit, Shredder Dust	None	None	Proton (AMP)
ELV age:	10 years	10 years or 500,000km	Not Specified	Min 3 years, inspection once in 2 years	Not specified	10 + 5 or 10 + 10 years	Proton (10 years)
Recycling Fees paid by:	Manufacturer & Importer pay when purchased	Market Driven (Collector pay last owner)	Market Driven (Collector pay last owner)	First owner, upon purchase	Market Driven (Collector pay last owner)	Market Driven (Collector pay last owner)	Market Driven (Collector pay last owner)
Operator Size:	303 Recycling operators, 5 shredding & Sorting plants	367 Recycling operators, 1 pilot recycling centre	226 Recycling operators, 7 shredding & Sorting plants	5000 Recycling operators, 140 shredding & Sorting plants	-	-	209 Recycling Operators, 0 Shredding & Sorting Plant
Effectiveness : (Recovery rate)	95%	90%	85%	85%	-	-	None
GDP Per-capita (USD):[f]	36,604	7,536	29,004	33,994	38,915	57,505	14,591

The closest Canadian Government have is the Canada-Wide Action Plan for Extended Producer Responsibility which was introduced in October 2009 [9]. ELV is indirectly included through products of “automotive products such as used oil, filters, batteries, refrigerants, brakes and transmission fluids”. It can be safe to state that Canada ELV recycling is driven by market demand as well as recycling awareness of Canadian citizen. Moreover, a complete framework of Canada ELV Recycling System is yet available which maybe one of the reasons why Canada still lacks in ELV recycling regulations. Plus there is no agency that tracks the number of ELV related materials and how they are handled except for British Columbia. Reference [9] also states that end-of-life is the least studied phase of vehicle lifecycle.

In Japan, recycling is made mandatory for all citizens and corporate entities by various laws implemented by the parliament. For the record, there are 80 million vehicles in Japan and 5 million is being disposed every year [11]. The Japan End-of-Life Vehicle Recycling law which was enacted in 2002 and came to force in 2005 was designed as a response with the increasing number of landfill due to vehicle waste in the island nation, and hike in vehicle recycling fees. The law systematically improves vehicle recycling through specification of car manufacturers and importers tasks as well as customers and government task.

The Japan Automotive Recycling System is designed to minimize illegal dumping possibilities by adopting a prior fee payment arrangement whereby the purchaser of a new vehicle must pay the recycling fee at the time of purchase, while the owner of an in-use vehicle must pay it at the time of the first periodic inspection. Moreover, the recent surge in industrial material prices has made otherwise abandoned ELVs valuable resources to be properly recycled. As a result, according to the Ministry of the Environment, the number of unlawful ELVs in Japan sharply declined from 126,000 units (92,000 units illegally stored and 34,000 units illegally dumped) in August 2001 to only 35,064 in March 2007.

One important contributor for this decline is the introduction of Licence Validity called Shaken which dictates the inspection interval of a vehicle shown in Table 2. The tough inspection was required to ensure public safety and environment sustainability via multiple point testing.

The rapid economic development of Taiwan and demand for improved quality of life had pushed the number of motor vehicles to the highest in the past 30 years. From the end of 1976 until the end of March 2009, the number of small passenger vehicles has increased from 170,984 to 5,668,581 and the number of motorcycles has increased from 2,009,698 to 14,382,923 vehicles.

Table 2: Shaken licence validity

Vehicle		**Expiry Date**	
		First	Subsequent
Truck	More than 8 tons	1 year	1 year
	Less than 8 tons	2 years	1 year
Bus		1 year	1 year
Taxi		2 years	1 year
Special Vehicles		2 years	2 years
Private car and Motorcycle		3 years	2 years

According to the statistics provided by the Recycling Fund Management Board Taiwan (RFMB), there are 303 ELV recycling operators in Taiwan and five shredding and sorting plants throughout the country. Taiwan recycling legislation is introduced since 1980s under the Waste Disposal Act. The law evolved from market driven activities to today's mandatory yet profitable business.

The volume of in-use vehicles in China will reach a staggering 32 million by the end of 2006 and the volume of End-of-Life Vehicles (ELVs) will be more than 1.5 million by the end of 2005 [12]. Recent data collected on 2011 indicated that vehicle market in China set a new record with sales of approximately 13,791,000 units in 2009, bringing in a total number of vehicles to 62,880,000 units [6]. This feat has pushed China to become the largest vehicle market in the world. It is estimated in year 2007, 3,506,000 vehicles are being scrapped.

Chinese lawmaker passed a regulation for disposal and recycling of ELV in 2001 a year after European Union introduced the law. The main feature; "Statute 307" is the declaration of ELV based on mileage accumulation and duration of service as shown in Table 3.

Korea produced around 3 million vehicles in 2001. Half of it is being exported to other countries leaving 1.5 million vehicles for the local market. In 2004, the number of vehicles in Korea stands at 14 million vehicles, and 500,000 ELVs are generated annually. 80,000 ELVs are exported as second-hand cars while the remainders are collected and processed at local dismantling facilities. Koreans follows the mandatory Act for Resource Recycling of Electrical / Electronic Products and Automobiles which requires the recycling of goods including vehicles. However, some developing countries, such as Malaysia, which are in the early stages of starting their ELV recycling system, lacks ELV recycling regulations [3].

3.2 Technology of ELV Recycling

Current ELV recycling process involves two major process; In-process which involves Dismantling and Shredding, and Post-Process which involves Material Recycling and Energy Reclamation. The dismantling process normally involves manual works of harvesting higher value parts for reuse market or reconditioned by remanufacturers. Usable parts are either sold directly to users or through second hand parts traders and service garages. Dismantling process usually is labour intensive and uneconomical which serves as an advantage for countries with low labour cost such as China. Advanced countries such as Japan use various tools to assist this activity and items harvested usually of high quality and undamaged.

For Shredding process, the ELV Body Shell, severely damaged and complex parts will be sent to shredding plant to churn it into smaller and manageable sizes. The ELV will be compressed before being fed into a giant rotating drum and being shredded by a set of rotating hammer. The output which known as Automobile Shredder Residue (ASR) is then sorted by its material type where metals and non-metals being separated using magnet. The process has higher efficiency if recyclability is integrated in the design phase but the challenge is vehicles were not designed to be recycled [13].

Materials sorted from ASR will be sent to respective recycling facilities such as electric arc steel melting furnace and plastic recyclers. Remaining ASR will be sent to incineration plants. Advanced countries such as Japan uses heat produced by incineration of ASR to generate electricity thus reclaiming the energy stored in the material [14].

Table 3: China classification of ELV

Vehicle Type	**Declared as ELV if:**
Mini-size commercial vehicles	Mileage exceed 300,000 km
Light commercial vehicles	Mileage exceed 400,000 km
Heavy, medium commercial vehicles	Mileage exceed 400,000 km
Passenger vehicles	Mileage exceed 500,000 km
Other vehicles	Mileage exceed 450,000 km
Mini-size commercial vehicles, including trailers and taxicabs*	Service period exceed 8 years
Light commercial vehicles and others	Service period exceed 10 years
* taxicabs for 19 passengers or less, light and mini-size commercial vehicles could prolong their service period up to half of the fixed number of years if they pass inspection for compliance with national vehicle exhaust standards.	

3.3 Current ELV Recycling System in Malaysia

Based on the first round of interview, a Current ELV Recycling System (Figure 1) had been engineered. In Malaysia, ELV can come from two sources; Vehicle from local market, and Vehicle imported from overseas. All local vehicles which intended for disposal will be required for Deregistration process. This process was meant to unregister the vehicle and to notify the government through Road Transport Department (also known as Jabatan Pengangkutan Jalan, JPJ) that the vehicle is no longer in use, and to strike out the record from JPJ together with all required tax payments. This process also prevents the vehicle from being used as an accessory for crime.

Malaysia also allows its local ELV Recycling companies to import ELVs from other countries. These vehicles will require clearance from Royal Malaysian Customs office. According to the law, any importation of vehicle will require an Importation Approval Permit (or AP). This also applies to ELV importation. In recent news, the government had announced that Open AP for vehicle importation will be abolished from 31st December 2015. It is still unclear whether this move will benefit ELV Recycler or not. The companies interviewed however are confidence that the government will be more lenient with this policy later. Normally, ELV recycler will choose and import the vehicle using their own means of transportation.

All vehicles are later being sent to the Dismantling facilities. In Johor alone, there are 32 dismantling facilities from the total 209 operators registered with the Malaysian Automotive Recyclers Association (MAARA) while the biggest ELV Recycler for local vehicle are in Perak, Malaysia. Here, the documents required for dismantling will need to be inspected for the purpose of verifying ownership on the vehicle. Reputable companies will not proceed if deregistration documents procured from JPJ are not present (for local ELV) but small scale dismantler often disregard this rule. Imported vehicles on the other hand are easier and only needed customs validation. Documents required are cross checked with the vehicle engine number and chassis number.

Later, the vehicle will undergo a de-pollution stage. Here, all fluids are being drained and stored for respective recycler. Battery, Mercury and other pollutant agents are removed to storage at this stage.

Finally, the vehicle will be dismantled. Useable parts are harvested and enter used spare parts market. Unusable or heavily damaged will be sorted by their respective material which will be sold to recyclers which meant for other industries. Parts which cannot be sold or recycled will be sent for disposal.

During participant interviews and observation, it is learnt that some recyclers do not adhere to the environmental law or guidelines. For an example, engine coolant are being discharged freely into the drains, and air-conditioning gas being freely released into the air. This will lead to a serious impact on the environment. The proposed framework will be required to address this issue as an incorporated part.

4 PROPOSED FRAMEWORK

European Union had targeted to have only 5% of a vehicle weight being sent to landfill by 2015. One of its objectives is to reduce the area required for landfill. Malaysia should also follow this target. If the framework is implemented successfully, the country will be beneficial in term of less land usage for ELV dumping ground, and a new source of economy for the nation. The Framework for ELV Recycling in Malaysia as shown in Figure 2 may assist Malaysia for this ambition.

Responsibility of ELV recycling should not be burdened on users alone. Manufacturers, retailers, recyclers, users as well as government should also work together to solve this problem. The framework empowers ELV recyclers and users to recycle and promote recycling activities. Apart from that, extended responsibility for manufacturers will also suggest them to improve their product through redesign, or simply adapting the design for recyclability and sustainability.

Important parties or stakeholders are also empowered to regulate the involved process. These stakeholders are the recycling associations, government entities, and user associations. Plus, environmental law currently exist will be integrated and internally enforced by the practitioner themselves. The ELV management board will also need to collect all information regarding ELV recycling within Malaysia.

All 6R criteria proposed by reference [15] is integrated within this framework. Table 4 shows responsibilities and explanation for each activity. Manufacturers have the responsibility to reduce and redesign the materials and parts respectively. They also indirectly involves in the parts reuse. Apart from that; recyclers, re-manufacturers, part dealers and incinerator also have their own responsibilities.

4.1 ELV Management Board

The ELV Management Board is a non-governmental body which act as regulator as well as auditors for ELV recycling operators. Their function is being modelled after the Taiwan ELV Recycling Fund Management Board.

The board may also assist the government in ELV policy making by providing information and studies regarding ELV Recycling (ELVR) activities. This body is modelled after Taiwan ELV recycling system which the government, recycling associations, and user associations work together to curb ELV problem. The board also have the responsibility of setting Standard Working Practices (SOP) for dismantling, depollution, parts evaluation, and shredding activities. They also may set the standard for safety of equipment and fixed/non-fixed facilities.

Table 4: Integrated 6R within framework for ELV recycling system

Activity	Responsibility	Explanation
Reduce	Manufacturer	Reduce material variability
Reuse	Part dealers/ manufacturer agents	Sale of reusable parts collected from dismantling process
Recycle	Recyclers	Recycle used materials into raw material for manufacturer/ other use
Remanufacture	Remanufacturer	Damage but still usable parts will be remanufactured/ recondition by OEM
Redesign	Manufacturer	Design or parts for easy processing
Recover	Incinerator	Regain the energy locked in the material

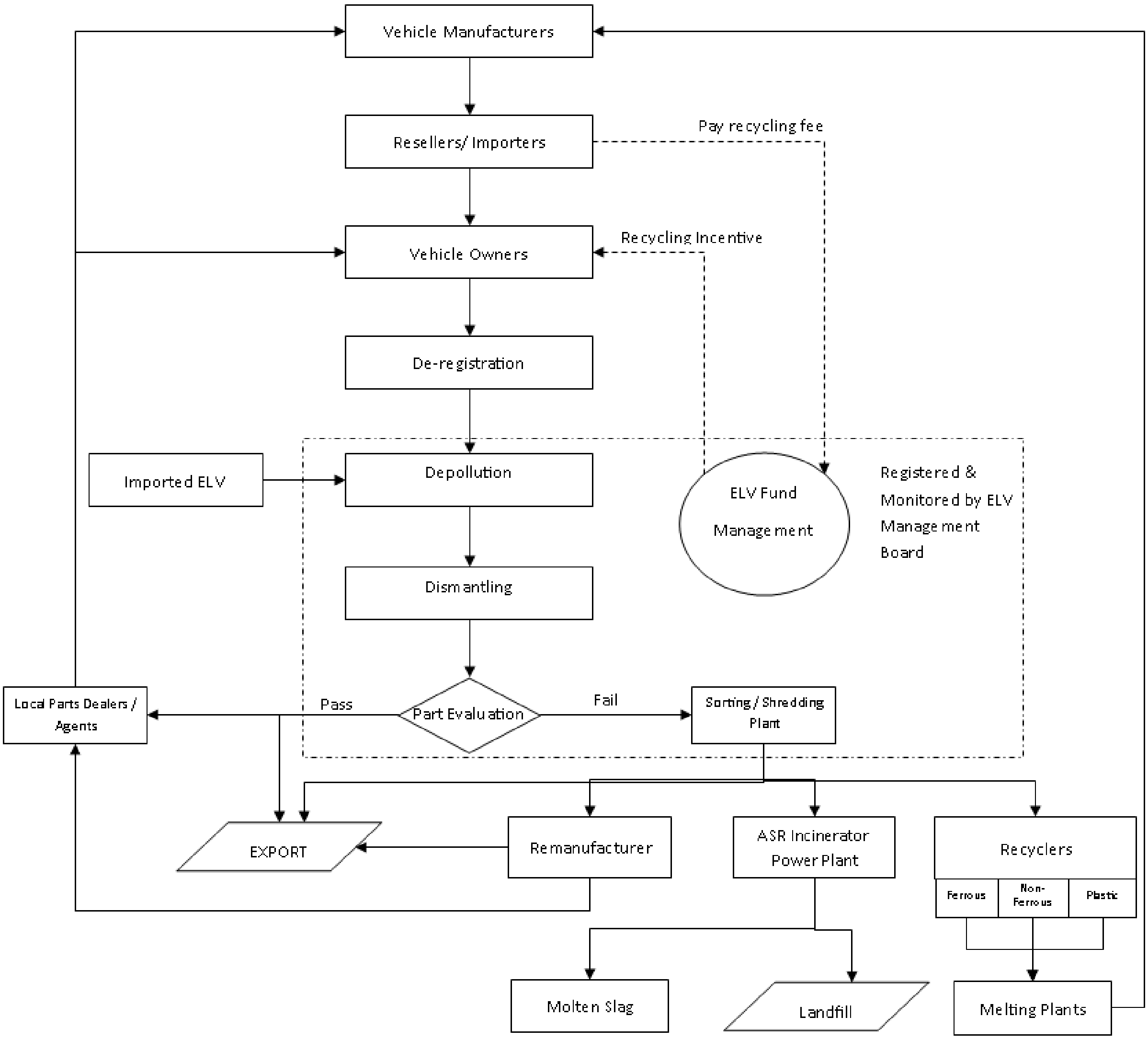


Figure 2: Proposed framework for ELV recycling system in Malaysia

Other responsibility is data collection such as number of local and imported ELVs being processed, ASR composition, economic value, recovery rate, or any data deemed useful for improvement of overall ELV recycling system and future sustainability studies.They also responsible in auditing, and provide training and expertise for ELV processors. This function was modelled by Canadian ELV recycling system which has its own Automobile Recycle Association University (ARAU), but here in Malaysia, it is better to integrate this function within the ELV Management Board. Apart from the functions listed, the board are also responsible for the ELV Fund. Recommended member for this board is:

1. MIROS : Malaysia Institute of Road Safety which represent the safety of road users.
2. JPJ : Road Transport Department to avoid fraud or crime related vehicles from being processed unknowingly.
3. Recyclers Association : represent recyclers.
4. Automobile Association Malaysia: represents the users interest in ELVR activity.
5. Sustainable Institute Malaysia: represents the environmental sustainability part, making sure all parties follow the environmental guidelines throughout the process.

4.2 ELV Fund Management

This body is responsible in managing fees related to ELV recycling system. They are required to provide monetary incentive for owners who wish to surrender their vehicle for scrapping. The fund management also model Taiwan system. Previously, the Malaysian government entrusted vehicle manufacturer for this fund (one-off incentive) but it’s only limited to new vehicle purchase from that manufacturer only.

4.3 Sorting and Shredding Plant

Shredding and sorting plant is the new addition to Malaysian ELV recycling system. Failed parts are being sorted according to its conditions. It may be remanufactured or recycled. Unrecyclable materials are originally sent to the landfill. This activity had increased the land usage that serves as dumping ground. The various sizes and shape of unrecyclable often breeding ground home by vectors such as vermin and mosquito. In the existing system, vehicles are being processed using blowtorch and metal saw to reduce the size. This activity is time consuming as well as unproductive. A dedicated shredding plant can increase this process and improve the sorting activities of the shredder dust by shredding it into small sizes. Valuable materials which are recyclable are being sorted by type and sent to respective recyclers. Automobile Shredder Residue (ASR) will be sent to ASR Incinerators.

4.4 ASR Incinerator Plant

Energy cannot be created or destroyed, but it can only be transferred. Energy used in producing the materials which are unrecyclable ASR can be extracted from its current condition via incineration. Incineration serves two purposes in ELV recycling system; to extract the energy and to reduce ASR weight. The by-product will be molten slag which can be used as brick or additional ingredient in concrete while the rest, if any will be sent to landfill.

5 CONCLUSION

This research project has presented the result of interviews conducted on Malaysian recycling companies with focus on ELV recyclers and part resellers. The main idea of the research is to provide a solution with win-win situation on the ever increasing number of ageing vehicle in Malaysia. It started with defining the current methodology of ELV management practice being applied in Malaysia. An interview had been done which involves 8 companies which consist of 5 recycling operators, 2 workshops, and 1 used tire reseller. Based on the information provided, a framework of current ELV recycling system had been developed. This framework was later sent to companies for validation which sees total acceptance which indicating the framework represents the real situation.

Rather than creating a framework from scratch, current practices and methodology successfully being applied in other countries such as Taiwan, China, Korea, Japan, Canada, and the European Union had been used in this research. It is followed by analysis of each system and a comparison between the key highlights was also done which saw most countries stated have governmental regulations except for Canada. It also includes, among other, the definition of an ELV by age by each country. This comparison also highlighted the most effective country, Taiwan to be the champion in ELV recycling with 95% of the vehicle initial weight being recycled. The strength of Taiwan ELV Recycling System or ELV Management was traced back to the foundation of an empowered ELV Management Board, which act as overseer for the whole process under the support from her government.

By compiling the advantages and covering any potential loopholes, a comprehensive framework had been developed which is an adaptation of ELV management success from around the globe. The Framework for ELV Recycling System in Malaysia will assist lawmakers and manufacturers for a better management of ELV in Malaysia before the problem becomes serious. It will also help the public to be more aware of their options regarding their vehicles.

6 ACKNOWLEDGMENTS

The authors wish to thank the Ministry of Higher Education Malaysia (MOHE), UTM and Research Management Center, UTM for the financial support to this work through the Research University Grant (RUG) funding number Q.J130000.2624.08J29.

7 REFERENCES

[1] BMW Group, (2002). Manual for recycling-optimizedproduct development. BMW Group.

[2] European Commission (2000). Directive 2000/53/EC of the European Parliament and of the Council on End-of-Life Vehicles. EU Directives.

[3] Amelia, L., Wahab, D.A., Che Haron, C.H., Muhamad, N. and Azhari, C.H. (2009). Initiating automotive component reuse in Malaysia, Journal of Cleaner Production. 17, 1572-1579.

[4] Malaysia Automotive Recyclers Association (2010). Market Review 2010, Statistic (2010).

[5] Chen, K. C., Huang, S. H., and Lian, I. W. (2010). The Development and Prospects of the End-Of-Life Vehicle Recycling System in Taiwan. Waste Management. 30, 1661-1669.

[6] Xiang, W. and Ming, C. (2011), Implementing extended producer responsibility: vehicle remanufacturing in China, Journal of Cleaner Production. 19, pg 680-686.

[7] Kim, K. H., Hyun, Tae J. H., Hoon, N., Chil S. Y., Hee H. J., Wook Y. T., Soo L. B. And Ho P. J. (2004). Management Status of End-Of-Life Vehicles and Characteristics of Automobile Shredder Residues in Korea. Waste Management. 24, 533-540.

[8] Sakai Shin-ichi, Yukio Noma and Akiko Kid (2007). End-of-Life Vehicle recycling and automobile shredder residue management in Japan, Journal of Material Cycles and Waste Management. 9(2), 151-158.

[9] Wordsworth, A. and Miller, S. (2011). Improving the Management of End-of-life Vehicles in Canada,CELA Publication, pp 784.

[10] The world bank, World Development Indicator 2011. http://data.worldbank.org/indicator/NY.GNP.PCAP.CD

[11] JETRO. (2006). Car Recycling Business in Japan, Japan Economic Report June-July 2006. Japanese Economy Division, Japan External Trade Organization.

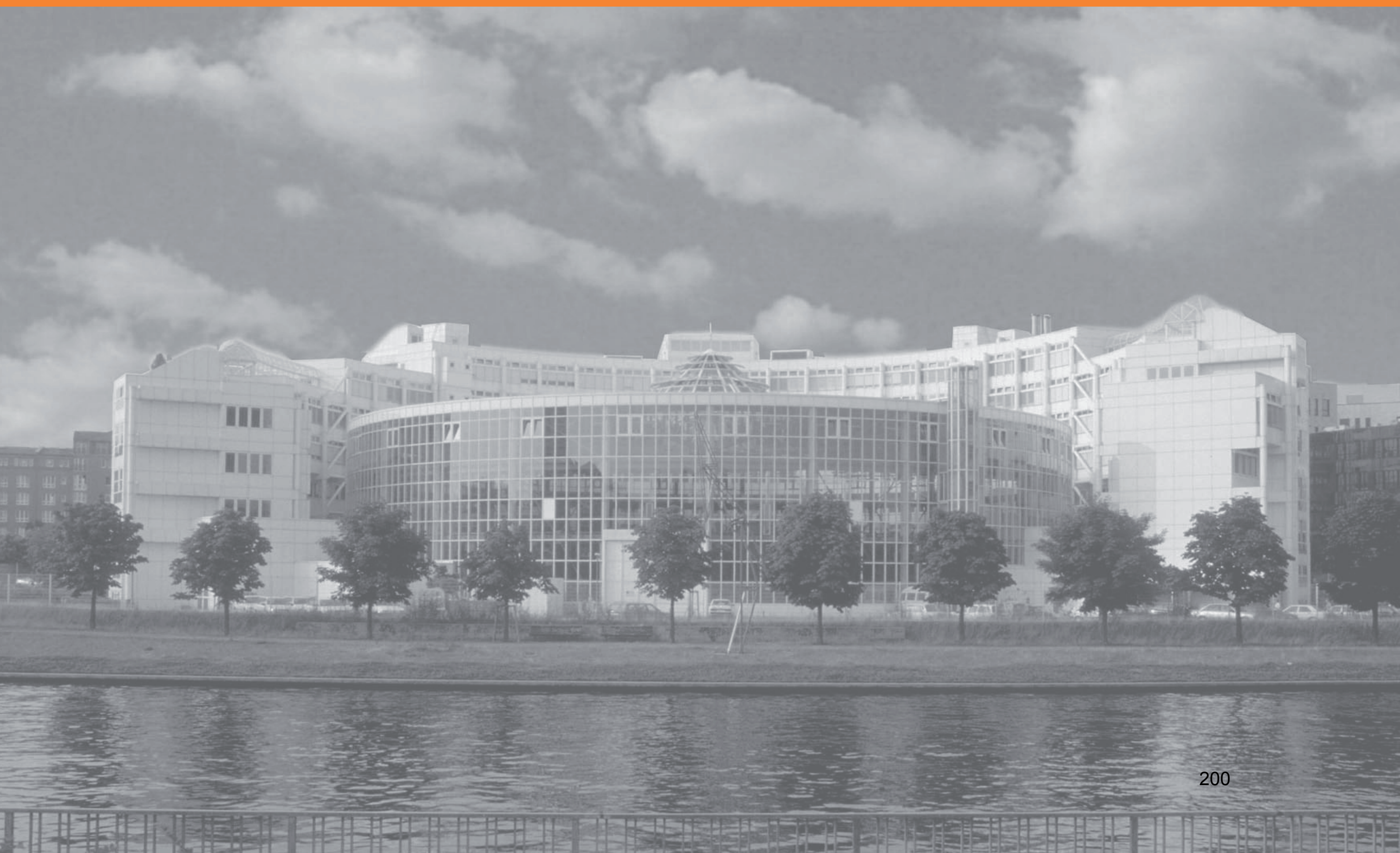
[12] Chen, M. (2005), End-of-Life Vehicle Recycling in China: Now and the Future, Journal of the Minerals, Metals and Materials, Society, Volume 57, Number 10, 20-26.

[13] Mat Saman, M. Z. and Blount, G. (2006), End Of Life Vehicles Recovery: Process Description, Its Impact And Direction Of Research, Jurnal Mekanikal. No 21, 40 – 52.

[14] Kojima, M. and Amit, J. (2008). Controlling Pollution In Small Scale Recycling Industries : Experiences In India And Japan. Promoting 3R in Developing Countries, IDE-JETRO 2008.

[15] Jayal, A. D., Badurdeen, F., Dillon Jr, O. W., & Jawahir, I. S. (2010). Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology, 2(3), 144-152.

Session 6
Lifecycle



GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

6.1 On improving the product sustainability of metallic automotive components by using the total life-cycle approach and the 6R methodology

X. Zhang, F. Badurdeen, K., Rouch, I. S. Jawahir

Institute for Sustainable Manufacturing (ISM), and Department of Mechanical Engineering,

University of Kentucky, U.S.A

Abstract

This paper presents a novel methodology involving the use of total life-cycle approach, including the Life-cycle Assessment (LCA) method, for improving the product sustainability performance of metallic automotive components. This involves consideration of all four life-cycle stages (pre-manufacturing - PM, manufacturing - M, use - U and post-use - PU), and integration of the 6R activities (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture). Various end-of-life (EOL) product scenarios - reuse, remanufacturing, and recycling - are modeled and analyzed within the chosen SimaPro LCA software environment. By using the recently established metrics-based Product Sustainability Index (*ProdSI*) methodology, final aggregated product sustainability scores for different product EOL options are generated. The validated *ProdSI* results provide options for improving the overall product sustainability by using the new evaluation methodology. This work also shows that a closed-loop material flow, and multiple life-cycles can be achieved through the use of this new methodology.

Keywords:

Automotive Products, Product Sustainability Index (*ProdSI*), 6R Methodology, Total Life-cycle Approach, Life-cycle Assessment (LCA)

1 INTRODUCTION

The auto industry, which continues to expand and grow, has in recent times recognized the need for embracing sustainable manufacturing because of the increasing demands, stricter regulations and growing concerns over resource utilization. According to the European Directive 2000/52/CE, the minimum requirement of resource recovery must be at least 95% of the average weight per vehicle and year, while the energy recovery must be a minimum of 10% of the average weight per vehicle and year [1]. Sustainable products, processes and systems constitute sustainable manufacturing, with the need for producing sustainable products forming the basis for sustainable manufacturing. For the purpose of producing more sustainable product generations, all processes involved in designing and manufacturing the products should be included. Consequently, traditional concepts are expanded to include total life-cycle of manufactured products, including pre-manufacturing (PM), manufacturing (M), use (U), and post-use (PU) stages [2]. Life-cycle Assessment (LCA) allows assessing the environmental consequences and potential impacts caused by the products [3]. However, to be able to comprehensively evaluate the products' sustainability behavior and sustainability performance, assessing their environmental impacts alone is insufficient. The other two sustainability components (economy and society) are also required when considering product sustainability. These three major components are also known as the Triple Bottom Line (TBL) [4]. Traditionally, the 3R concept (Reduce, Reuse, and Recycle) was focused on reducing the use of virgin materials and resources, promoting reuse activities with recycling of products at the end of their life. To enable significant improvement of the overall product sustainability, a novel methodology-the 6R methodology, involving Reduce, Reuse, Recover, Redesign, Remanufacture, and Recycle-has been introduced to incorporate multiple life-cycles of a product and a closed-loop material flow [5]. To facilitate effective decision making in developing sustainable products, it is essential to evaluate the sustainability behavior of the proposed products comprehensively. The recent Product Sustainability Index (*ProdSI*) methodology offers such a comprehensive evaluation capability [6]. It is metrics-based and is built on a five-level hierarchical structure. Computing the final *ProdSI* score can be completed via a sequence of steps: data normalization, weighting, and score aggregation.

The previous work by the authors has shown that EOL product recycling contributes towards improving the product sustainability of metallic automotive components [7]. In this paper, a novel method incorporating the total life-cycle approach including the LCA method, the TBL, and the 6R methodology is presented for improving the product sustainability performance of metallic automotive components with multiple end-of-life (EOL) product options. Continuing the previous work [6-7], two additional product EOL scenarios – reuse and remanufacturing, are included in this study to present final product sustainability scores for a total of three different product EOL options – reuse, remanufacturing, and recycling. With the validation of the *ProdSI* results, the overall product sustainability shows improvements at various levels, which verify that using product EOL strategies improve the overall product sustainability. Ultimately, this work contributes towards implementing a near-perpetual material flow with multiple life-cycles.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

2 BACKGROUND

Due to the recent awareness of the significance of manufacturing sustainable products, during the last few years a range of methods for assessing the product sustainability has been developed. A comprehensive review of the most commonly used methodologies for product sustainability assessment was presented by Feng and Joung [8].

Various approaches are used in the auto industry to measure and evaluate the sustainability performance of vehicles. The product sustainability index (PSI) method, developed by Schmidt and Butt [9], was based on LCA impact assessment categories. It includes eight key environmental indictors across three major aspects of the product sustainability. The economic indicators are from Life-cycle Costing (LCC) assessment method. The societal indicators are aimed at evaluating the safety and mobile capability of a product. This methodology was further applied to two of their vehicle models. Based on the sustainability scoring method developed by de Silva et al. [10], Ungureanu et al. [11] developed a new methodology to quantitatively assess the potential benefits of using aluminum alloys for manufacturing of an autobody. This method involves six major elements of the Design for Sustainability (DfS): environmental impact, functionality, manufacturability, recyclability and re-manufacturability, resource utilization/economy and societal impact [2]. Each of these elements was sub-divided into several corresponding sub-elements. Different levels of influencing factors were categorized based on their significance to the product. The level of importance of each sub-element was assigned with high, medium, or low weights. Finally, sustainability scores of two different materials (steel alloy and aluminum alloy) were computed and their levels of sustainability performance were compared. This method can also be used for comparing the same family of different generation of products. A set of initial key performance indicators (KPIs), proposed by Amrina and Yusof [12], was specifically developed for the auto industry to evaluate product sustainability. The new methodology involving total life-cycle cost analysis, proposed by Ungureanu et al. [13], was aimed at developing a new sustainability model to quantitatively evaluate the total direct cost across the entire life-cycle of a vehicle. The environmental impact caused by using a light-weight material, aluminum alloy, for auto body was presented.

Despite technical merits, the above-reviewed methodologies are not efficient enough to provide or even define the product sustainability comprehensively. They do not cover all life-cycle stages of the products, and they mostly focus on M and/or U stages at the design stage. Neither have considered all three major areas of the TBL as they mostly assess economic and/or environmental impacts caused by the products. Also, very limited research has been reported on improving a product's sustainability through enhancing product EOL activities.

The recently developed *ProdSI* methodology provides a comprehensive assessment for product sustainability [6]. The new method proposed in this paper, integrating total life-cycle approach, the TBL, and the 6R methodology, enables significant improvement in the overall product sustainability assessment of metallic automotive components via application of different EOL product options.

3 THE 6R METHODOLOGY

This section presents a novel approach for improving the overall product sustainability performance of metallic automotive components. It involves the consideration of all four life-cycle stages of the products, including LCA method, and integration of the 6R activities - Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture.

3.1 Terminologies of the 6R Methodology

Based on the definitions of the 6R activities developed by the Institute for Sustainable Manufacturing (ISM) at the University of Kentucky, descriptions to these terminologies that are relevant to the study are given below, in order to better assist the illustration the 6R decision flow. The *Reduce* activity aims at reducing the use of various kinds of materials and resources, and reducing the generation of wastes and emissions. A functional component can be *reused* by utilizing them in a new product, or as a component to make the same new products or different product assemblies, after this useable component is disassembled from its old product. By using remanufacturing processes, a worn out/broken/used product can be restored to its original specifications. The worn out/used product can also be further modified and upgraded with new specifications by redesigning the EOL product into a new product. The *remanufactured* product will become a functional unit that preserves equivalent and sometimes even superior features in terms of quality and functionality, reliability and performance, lifetime and appearance. It should also at least endure another full life-cycle. EOL products made of recyclable materials can be converted into new materials through recycling processes; otherwise, non-recyclable materials would be disposed to landfill. Recycled materials can subsequently be used in the form of raw materials to make either the same or different new products. *Recycling* can also be applied to recover energy from EOL products in some cases. *Redesign* can be performed for the purpose of increasing the use of recovered materials or components from their earlier EOL generations to produce improved next generation products, either the same or totally different products. From the perspective of functionality, the newly redesigned products should show superior features and performance compared with the older generations. Their related processes across the entire life-cycle should consume fewer resources and generate fewer wastes as well.

3.2 The 6R Decision Flow for Metallic automotive Components

The virgin materials are formed to chunk pieces at the PM stage. The components produced and assembled into products at the M stage go through its U stage. When the valuable life of metallic automotive components comes to an end at this stage, several decisions for various 6R activities can be made at its PU stage. Figure 1 illustrates the 6R decision flow for metallic automotive components. If the material cannot be recovered for use as either material or energy, then it goes to landfill. If the EOL products are recoverable, the first activity to consider is reuse. After a preliminary inspection and a full cleaning, components eligible for reuse can be directly used for assembly to make new products. If the components are not qualified for reuse, remanufacture is the next activity to consider. If the components do not have serious defects such as damaging cracks, and if their original specifications can be

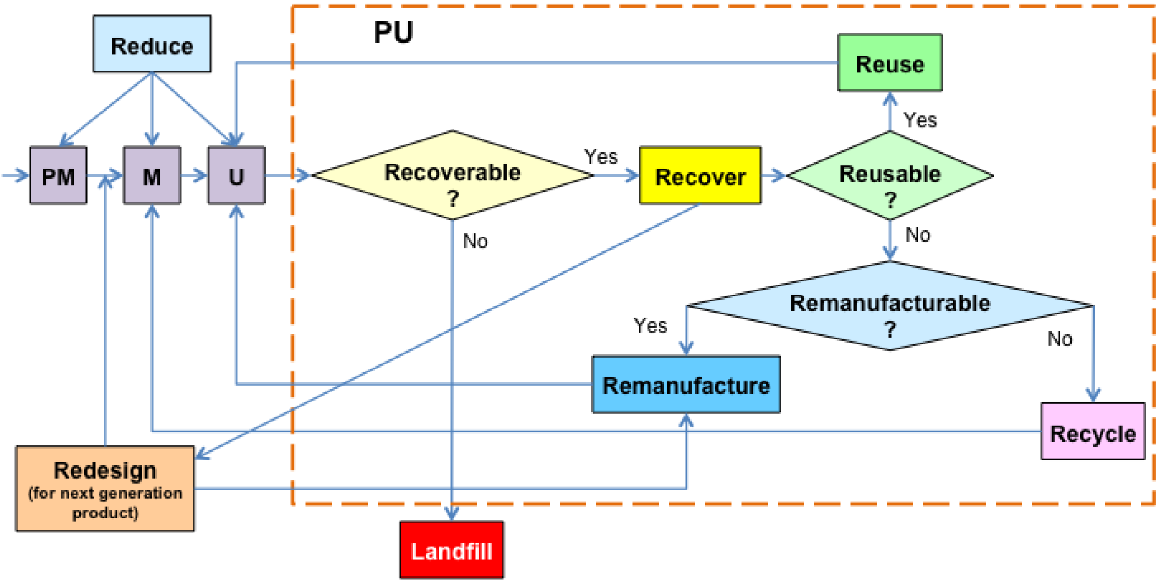


Figure 1: The 6R decision flow diagram across four life-cycle stages of metallic automotive components

restored by remanufacturing, they can be transported to the manufacturing plant after the material deposition process. If the components suffer from serious defects that they cannot be restored to their original specifications by means of remanufacturing, then material recycling will be an alternative practice. After a sequence of recycling processes, the materials can be recovered and reused in the form of raw materials to make either the same or different products. In this case, either the materials or the components can be reused within a closed-loop. Ultimately, virgin materials would be no longer needed to produce the next generation products.

Recovered material can also be used either in manufacturing or in remanufacturing through redesigning of next generation products that can use the recovered end-of-life material from the previous generation of products. Multiple closed-loop material flow could be achieved with this 6R methodology.

4 TOTAL LIFE-CYCLE MODELING OF METALLIC AUTOMOTIVE COMPONENTS WITH VARIOUS PRODUCT EOL OPTIONS

In previous work, one of the EOL product options, recycling the EOL metallic automotive components-was presented [7]. In order to comprehensively examine the effects on using different 6R-based EOL product activities, this section presents the analysis using two other Rs, the reuse and remanufacturing.

The modeling work is based on the same assumption as in [7] that the chosen product is a stand-alone manufactured component from a single material. All outputs of 6R activities are assumed to be used for producing the same components, not for other products. Metallic automotive components are made of alloy steel. The proportions of components reused, remanufactured and recycled are assumed to be consistent with the rates established for each of these activities. The metrics selected for the analysis and the *ProdSI* evaluation stay unchanged as well. The modeling work is carried out within the LCA software environment SimaPro 7.3. Eco-indicator 99 (H) is used as the assessment method.

4.1 Modeling the Reused EOL Products

Figure 2 illustrates a map of processes needed for four life-cycle stages to reuse the EOL products.

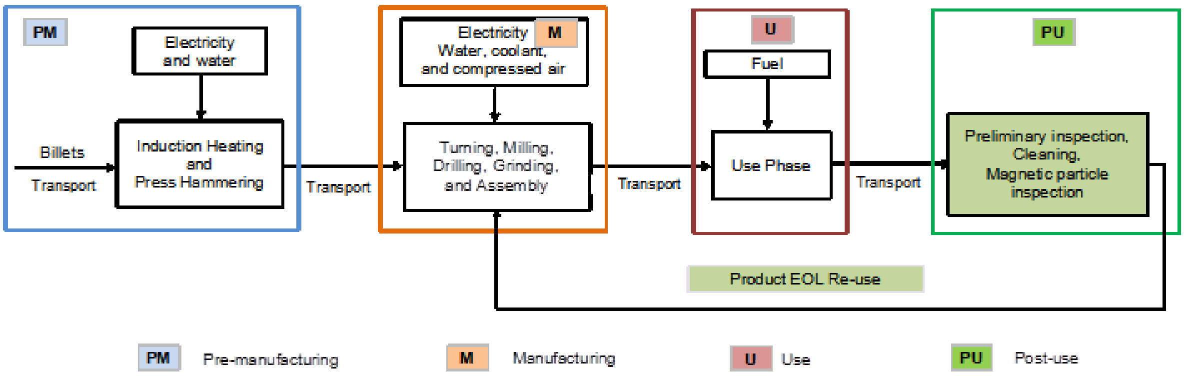


Figure 2: Process map across four life-cycle stages for reusing EOL products.

Mass of Hazardous Material Use

The same approach discussed in [7] was followed. Due to space limitations, the detailed process of computation cannot be presented in the paper. Calculated results show that in the PM and M stages the mass of hazardous material use decreases linearly as a direct effect of fewer virgin materials used.

In the M stage, the mass of hazardous material use contains mainly used coolant; it also includes other forms of hazardous contents, such as fumes and metal debris. The used coolant is 100% recycled in the manufacturing plant. Value for the U stage stays zero as the components do not generate any hazardous materials during its U stage. Constant trends apply to all subsequent individual metrics for both M and the U stages analyzed in this study. In the PU stage, the amount of hazardous material use increases as the ratio of reused EOL product increases. This is because more product EOL activities are involved along with the increased reuse of old products. The total mass of hazardous material use for four life-cycle stages drops linearly when the ratio of reused EOL product varies from 0% to 90%. This trend can be represented equation (1), where the mass of hazardous material use for reusing EOL products is expressed as a function of the ratio of reused EOL product *(x_1).* The function is obtained by fitting a curve to the trend line. The mass of hazardous material use is measured as mg/ unit.

$$y^{reuse}_{mh\_total} = -40108\, x_1 + 40129 \quad (1)$$

Energy Use

Calculated results also show that in the PM and the M stages the amount of energy use is a combination for both, due to the fact that less numbers of products are manufactured when some EOL components are reused. Consequently, reduced need for virgin materials results in a decrease in the energy use at these two stages. In the PU stage, the energy use increases linearly when the ratio of reused EOL product increases. The total energy use for four life-cycle stages decrease as expected when the ratio of reused EOL product varies from 0% to 90%. This trend can be expressed by equation (2). The energy use is measured as MJ/ unit.

$$y^{reuse}_{eu\_total} = -149.4\, x_1^2 - 269.67\, x_1 + 9326.1 \quad (2)$$

Water Use

Also, in the PM and the M stages, the water use decreases linearly because it is directly related to the amount of virgin materials used. In the PU stage, the water use shows an increase as the ratio of reused EOL product increases to 20%. The growth in water use is due to the effect of turning on the entire EOL operating system. Then, it reduces slowly along with the percentage of reusing EOL products changes from 20% to 90%. Total water use for four life-cycle stages increases as the ratio of EOL product reused increases to 20%, and then it drops as the percentage increases to 90%. This trend can be expressed by equation (3). The water use is measured as Kg/ unit.

$$y^{reuse}_{wu\_total} = 3061.7\, x_1^3 - 5210.9\, x_1^2 + 1843.1\, x_1 + 637.52 \quad (3)$$

Greenhouse Gas Emissions

In the PM and the M stages, the Greenhouse Gas emissions decrease linearly due to the decreasing amount of virgin material used. It can be observed that the major contribution of the GHG emission comes from the U stage, because a vehicle consumes a large quantity of energy. The Greenhouse Gas emissions in the PU stage shows an increase when the ratio of reused EOL product increases to 20%, then it drops slowly when the percentage of reusing EOL products changes from 20% to 90%. The total Greenhouse Gas emission for four life-cycle stages shows a linear decrease, and it can be expressed by equation (4). The the Greenhouse Gas emission is measured as MJ/ unit.

$$y^{reuse}_{ge\_total} = -107.93\, x_1 + 278479 \quad (4)$$

Direct Cost

Table 1: Unit cost used in this study

Direct Cost	Unit Price
Labor cost	$15/hour
Material cost	$2.12/Kg
Electricity cost	$0.0505/kWh
Water cost	$1.52/ton

Table 1 provides the unit costs that are used to calculate the total direct cost in this study. The same data are used for scenarios of remanufacturing and recycling EOL products. The labor cost is directly proportional to the hours of workforce involved in the processes at each product life-cycle stage. All the other economic metrics selected - material cost, energy cost, and water cost - are directly related to the amount of usage for each metric. The total direct cost can be computed by summing up the individual costs for each varying ratio of reused EOL product. A decreasing trend can be observed. This trend can be expressed by equation (5). The direct cost is measured as $/unit.

$$Y^{reuse}_{dc\_total} = -41.51 x_1 + 184.19 \quad (5)$$

4.2 Modeling the Remanufactured EOL Products

In the PM stage, induction heating and press hammering are the processes needed to transform steel billets into chunk pieces. In the M stage, manufacturing processes involve turning, milling, drilling, grinding, and product assembly. In the PU stage, remanufacturing processes include preliminary inspection, cleaning, magnetic particle inspection, and material deposition. This is the stage where the original states of the product can be restored.

Mass of Hazardous Material Use

In the PU stage, the amount of hazardous material use shows a increase when the ratio of remanufactured EOL product increases. A larger slope of increase can be observed when comparing the scenario of reusing the old products. This is because powered steel deposition is the additional process needed for remanufacturing. The total hazardous material used for four life-cycle stages shows a linear decrease when the ratio of remanufactured EOL product varies from 0% to 90%. This trend can be expressed by equation (6), where the mass of hazardous material use for remanufacturing EOL products is expressed as a function of the ratio of remanufactured EOL product *(x_2)*.

$$y^{remfred}_{mh\_total} = -40025\, x_2 + 40129 \qquad (6)$$

Energy Use

In both the PM and the M stages, the amount of energy use decreases because fewer virgin materials are involved when EOL products are remanufactured. In the PU stage, having more remanufacturing activities involved leads to an increase in energy use when the ratio of remanufactured EOL product increases. This is especially due to the process of thermal spray for powered material. The total energy use for four life-cycle stages increases when the ratio of remanufactured EOL product varies from 0% to 90%. This trend can be can be expressed by equation (7).

$$y^{remfred}_{eu\_total} = -148.7\, x_2^2 - 880.85\, x_2 + 9326.1 \qquad (7)$$

Water Use

In the PM and the M stages, the water use decreases linearly as a result of remanufacturing old products. In the PU stage, the water use shows a large increase as the ratio of remanufactured EOL product increases, since large quantity of water is needed for the cleaning process. Total water use for four life-cycle stages increases when the ratio of remanufactured EOL product varies from 0% to 90. This variation can be expressed by equation (8).

$$y^{remfred}_{wu\_total} = -1116.7\, x_2^2 + 3447.5\, x_2 + 684.07 \qquad (8)$$

Greenhouse Gas Emissions

In the PM and the M stages, the Greenhouse Gas emissions decrease linearly because of less involvement of the virgin materials. In the PU stage, the Greenhouse Gas emission shows a slight increase. The total Greenhouse Gas emission for four life-cycle stages decreases when the ratio of remanufactured EOL product varies from 0% to 90%. This linear trend can be expressed by equation (9).

$$y^{remfred}_{ge\_total} = -99.7\, x_2 + 278479 \qquad (9)$$

Direct Cost

The total direct cost shows a slight decrease. Comparing with the value of the scenario for reusing the EOL products, the slope of decrease is smoother. This is because more energy, water, and labor are needed for the additional material deposition process. This trend can be expressed by equation (10).

$$Y^{remfred}_{dc\_total} = -3.77 x_2^2 - 2.46\, x_2 + 183.94 \qquad (10)$$

5 PRODUCT SUSTAINABILITY ASSESSMENT FOR DIFFERENT PRODUCT EOL SCENARIOS BY USING THE *PRODSI* METHODOLOGY

By using the Product Sustainability Index (*ProdSI*) methodology to assess the product sustainability performance, scores for sub-indices and the final *ProdSI* are calculated for each EOL product option. To effectively compare the differences in the product sustainability among various EOL product activities, data normalization, weighting, and data aggregation methods are made consistent. Measurements of 100% landfill are used as basis for data normalization since it is considered as the worst-case scenario. Equal weighting is applied throughout the computation, when values are aggregated to the next higher level. From the results shown in Table 2, strength and weakness of the areas of product sustainability with each EOL product options can be observed. The comparison is also visually presented in Figure 3. The numerical range 0 to 10 represents the level of progression. The higher the score, the more sustainable the product is. Score 8 represents an "excellent" status, score 6 stands for "good" condition, score 4 represents an "average" level, and score 2 means "poor" condition. Total *ProdSI* scores indicate that disposing the products at their EOL is the least sustainable EOL activity while reusing the old components is the most sustainable practice as expected. Comparing between the options of remanufacturing and recycling of the EOL products, material recycling has turned out to be more sustainable than component remanufacturing in this case, based on the assumptions made prior to modeling four life-cycle stages of metallic automotive components.

Table 2: Sub-indices and *ProdSI* score comparisions

	100% Landfill	80% Recycling	80% Re-mfg.	80% Re-use
Economy	5.90	4.84	3.50	7.40
Environment	3.42	6.28	6.01	8.76
Society	6.48	7.68	8.00	7.98
ProdSI	5.25	6.27	5.84	8.05

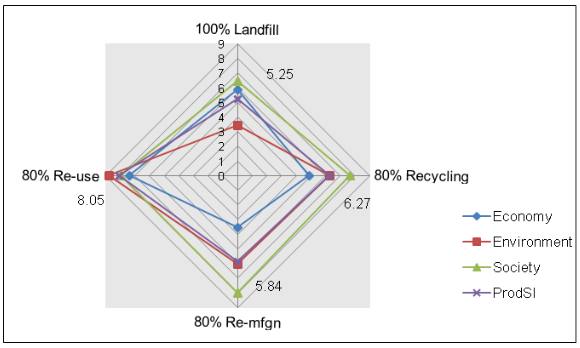


Figure 3: Score comparison for sub-indices and the final *ProdSI* for different EOL product options

6 DISCUSSION

Both analyses from the LCA models and the product sustainability scores validate and prove that the overall product sustainability of metallic automotive components can be improved by applying the 6R methodology. Such achievement can be made from applying a single 6R activity or multiple 6R activities. In this study, the results indicate that products would become more sustainable, when higher ratios of EOL product activities are chosen.

The total values of mass of hazardous material use, energy use, water use, Greenhouse Gas emission, and direct cost show approximate linear relations because the individual metrics selected in the study are directly related to the amount materials involved. However, non-linear correlations will present when other metrics are considered, such as indirect costs, and health and safety related issues.

Metallic automotive components in this study are made of a stand-alone ferrous material. The 6R decision flow and the life-cycle models are product- and industry-specific. When this methodology is applied to another family of products or another industry, the 6R decision flow and LCA models will change. When using this methodology to analyze a product made of composite materials, it will require a much more complex analysis. A combination of multiple LCA models for each type of material involved will be needed. Consequently, its analysis and *ProdSI* evaluation processes should be done for each life-cycle model simultaneously.

While making a complicated product sustainability evaluation is achievable, putting the methodology into practice in the industrial world can be challenging. Even though it is well recognized that enhancing product EOL management is a more sustainable practice, disregarding any product EOL activities is what is often observed, unless it is restricted by regulations. Quite commonly, it is because of technical issues and/or economic reasons.

In previous work, only EOL product recycling was addressed. The rest of the 6R activities are presented in this paper. Interactions and analysis of all 6Rs are completed comprehensively. This is achieved from assessing the effects of all possible EOL product activities simultaneously. As a result, mathematical equations for individual sustainability metrics are expressed with multiple independent variables, which can be used as decision variables for setting up a percentage mix optimization problem. Finally, an optimal mix of product EOL activities can be obtained. Moreover, since the *ProdSI* methodology is metrics-based, and the 6R activities and the individual metrics are interrelated, such mathematical and analytical models can be further used to develop product sustainability optimization models.

7 CONCLUSIONS

In this paper, a new approach for improving the overall product sustainability of metallic automotive components is presented. This method utilizes a total life-cycle approach, the TBL, and the 6R methodology. Four life-cycle stages of metallic automotive components are modeled and analyzed within a LCA software environment. The product sustainability score for each EOL product option is computed by using the *ProdSI* methodology. The *ProdSI* scores confirm that the overall product sustainability of metallic automotive components can be improved from applying EOL product activities. The results provide options to EOL product strategies. This study also shows that a near-perpetual material flow can be achieved, and a single product life-cycle can be expanded to a multiple life-cycles through the use of this new methodology. Therefore, the research results confirm that applying product EOL strategies increase overall product sustainability. Also, the approach presented in this paper provides a basis to the development of multi-objective product sustainability optimization models.

8 REFERENCES

[1] EU, 2000, Directive 2000/53/EC of The European Parliament and of The Council of 18 September 2000 on End-of-life Vehicles, The European Parliament and The Council of The European Union.

[2] Jawahir, I.S., Rouch, K. E., Dillon, O. W. Jr., Joshi, K. J., Venkatachalam A. and I.H. Jaafar, 2006, Total Life-cycle Considerations in Product Design for Manufacture, A Framework for Comprehensive Evaluation, Proc. TMT 2006, Barcelona, Spain, 1-10.

[3] ISO 14040, 2006, Environmental Management: Life Cycle Assessment-Principles and Framework, International Organization for Standardization.

[4] Elkington, J., 1998, Cannibals with Forks: The Triple Bottom Line of the 21st Century Business, USA, New Society Publishers.

[5] Joshi, K., Venkatachalam, A., Jawahir, I. S., 2006, A New Methodology for Transforming 3R Concept into 6R Concept for Improved Product Sustainability, Proc. IV Global Conf. on Sustainable Product Development and Life Cycling Engineering, San Carlos, Brazil, 3-6.

[6] Zhang, X. Lu, T., Shuaib, M., Rotella, R., Huang, A., Feng, S. C., Rouch, K., Badurdeen, F., Jawahir, I. S., 2012, A Metrics-based Methodology for Establishing Product Sustainability Index (*ProdSI*) for Manufactured Products, Proc. 19th CIRP Conference on Life Cycle Engineering, Berkeley, CA, USA, 435-441.

[7] Zhang, X., Shuaib, M., Huang, A., Badurdeen, F., Rouch, K., Jawahir, I. S., 2012, Total Life-cycle Based Product Sustainability Improvement: End-of-life Strategy Analysis for Metallic Automotive Components, Proc. 10th Global Conf. on Sustainable Manufacturing (GCSM 2012), Istanbul, Turkey.

[8] Feng, S.C., Joung, C., 2010, Development Overview of Sustainable Manufacturing Metrics, Proc. 17th CIRP International Conference on Life Cycle Engineering (LCE 2010), Hefei, China.

[9] Schmidt, W. P., and Butt, F., 2006, Life Cycle Tools within Ford of Europe's Product Sustainability Index, Int. J. Life Cycle Assessment 11/5: 315-322.

[10] de Silva, N., Jawahir, I.S., Dillon, O.W., Russell, M., 2009, A New Comprehensive Methodology for the Evaluation of Product Sustainability at the Design and Development Stage of Consumer Electronic Products, Int. J. Sustainable Manufacturing, 1(3): 251-264.

[11] Ungureanu, C. A., Das, S., and Jawahir, I. S, 2007, Life-cycle Cost Analysis: Aluminum versus Steel in Passenger Cars, Proc. TMS Conference, 11-24.

[12] Amrina, E. and Yusof, S. M., 2011, Key Performance Indicators for Sustainable Manufacturing Evaluation In Automotive Companies, Proc. 2011 IEEE, IEEM. Singapore, 1093-1096.

[13] Ungureanu, C. A., Das, S., and Jawahir, I.S., 2007, Development of a Sustainability Scoring Method for Manufactured Automotive Products: A Case Study of Auto Body Panels, Proc. IMECE 2007, Seattle, WA.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

6.2 Life Cycle Inventory (LCI) analysis of the Sicilian artistic and traditional ceramics as a tool for sustainable manufacturing

A. Lo Giudice[1], C. Mbohwa[1], M. T. Clasadonte[2]

[1] Department of Quality and Operations Management, Faculty of Engineering and the Built Environment, APB Campus, University of Johannesburg, South Africa

[2] Department of Economics and Business, University of Catania, Italy

Abstract

In the last few decades, greater attention is being paid by the Italian industrial ceramics sector to the environmental impacts related to ceramics production cycle and many companies have acquired voluntary environmental certifications (ISO 14001 or EMAS) or labeling (Ecolabel or EPD). This is not the case with the artistic ceramics sector in which few companies are certified. One of the most common and used tool for evaluating the environmental impact of products is the Life Cycle Assessment (LCA) methodology. This paper presents the preliminary results from a Life Cycle Inventory (LCI) analysis of the artistic ceramics sector in Caltagirone (Italy). Representative life cycle inventories are essential for any good quality LCA. They represent the fundamental blocks for compiling the full LCA of the ceramics production process, hence promoting environmental sustainability.

Keywords:

Ceramics, Environmental hotspots, Inventory, Sicily

1 INTRODUCTION

The Italian ceramics sector mainly produces the following five main products: floor and wall tiles, product for domestic and ornamental purpose (ceramics for daily or interior decoration use), terracotta products (such as bricks, roof tiles), refractory materials (for industrial technological use) and saniratyware. Besides these “official” product areas, it is possible to identify another one: the artistic and traditional ceramics products. For certain Italian regions, it characterises (sometimes also in a significant way) the local economy, giving the sector great importance even if the statistical data are not comparable to those of the other products.

The Italian ceramic tile industry, in particular, enjoys an unrivalled world leadership position, accounting for 9% of world and 40% of the European Union's tile production. Investment levels are at 5.5% of turnover, confirming the Italian ceramic industry's commitment to carry on its supremacy into the new millennium. These results are built on the Italian ceramic tile industry's tradition, constantly fuelled by technological innovation and product developments.

Due to the accumulated side-effects of its activities, (energy, water and non-renewable raw materials consumption, water, air and soil pollution) this industry was one of the first to develop a strong environmental awareness and to seek to combine environment protection, health and safety with sustained market competitiveness. Over the past decade the industry has shown a shift towards sustainable development projects through integrated and comprehensive standards and regulations (ISO 14001 and EMAS Regulation; environmental labels such as Ecolabel or Environmental Product Declaration, EPD) that take account of the causes of environmental impact and the tools to be used for preventing or, at least, minimising it. The Italian ceramic industry’s world leadership position is, therefore, not limited to production but includes also a commitment to achieving extremely low levels of environmental impact and to fully respecting the ecological equilibrium [1].

The Life Cycle Analysis (LCA) methodology, which is the most common internationally accepted and acknowledged tool for assessing and demonstrating the environmental behaviour of a system meets the needs of both production and the environment. This methodology can be specifically tailored to the ceramic tile sector and can be used to identify and evaluate the positive and negative effects that the various production techniques have on the environment and, hence, researchers can draw up new prevention and protection measures. The parameters analysed on the basis of the LCA are materials, energy, gaseous emissions and waste.

The literature review shows many examples of the application of LCA to the industrial ceramic sector. For example, the following studies have been conducted:

- Nicoletti et al. focused on the comparative Life Cycle Assessment of flooring materials (marble vs. tiles) [2];
- Bovea et al. analysed the environmental performance of ceramic tiles and the possible improvements related to the productive cycle [3];
- Bovea et al. evaluated the environmental performance of the process currently used to package and palletize ceramic floor and wall tiles and proposed and analysed improvements from an environmental point of view [4];
- Bovea et al. conducted a Cradle – to – Gate study of red clay for use in the ceramic industry [5];
- Breedveld et al presented a simplified LCA to assess the overall environmental effects of fabric filter in Italian ceramic tiles production. Furthermore, they calculated the eco-efficiency of such filters, the additional cost per unit reduction of emissions [6];

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

- Mahalle, conducted a comparative LCA to compare and contrast the environmental performance of hardwood flooring with some alternative flooring types: carpet, ceramic floor tiles, vinyl flooring, cork, and linoleum. [7];
- Almeida et al. proposed the application of the Environmental Product Declaration (EPD) in ceramics materials as a sustainability tool [8].

The huge environmental commitment highlighted in the industrial ceramics sector cannot be found as yet among the artistic and traditional ceramics sector despite the fact not only it is an economic and productive sub-sector but that it also has historical and artistic value.

Very few enterprises working in this sector have adhered to ISO 14001/EMAS environmental certification for their productive processes. Regarding the product certification, such as EPD, no examples can be recorded in the Italian sub-sector, even though there is a growing interest coming from the stakeholders regarding this type of voluntary environmental labels. If well managed, product certification can represent a valid instrument of enhancing and differentiation of the sub-sector's products on the market.

In this context the aim of this paper is to develop life cycle inventories one of the most common artistic and traditional ceramic products: the ceramic dishes. The current literature review shows no examples of the application of the LCA methodology to this sector.

2 THE ARTISTIC AND TRADITIONAL CERAMICS SECTOR: THE DISTRIC OF THE CERAMICS OF CALTAGIRONE

The "First National conference on ceramics" held in Rome in 2008 highlighted that the Italian artistic and traditional ceramic sector is going through an evident decline measured in terms of the reduction in the number of employees and of enterprises.

Italy has a big tradition of artistic and traditional ceramics production. The ceramic art craft plays an important role in contributing to local production volume, and culture and the territory that are related to it. While the art of ceramics is widespread among all the Italian regions most of them are located in Sicily, Campania, Veneto, Tuscany, Emilia Romagna and Umbria [9].

In Sicily, despite the crisis in the industry, the arts and traditional ceramics industry still plays a crucial role in the Sicilian economy. It is one of the few production systems considered an area of excellence in the region, together with the marble, agri-food, engineering and electronics industry. Two industrial districts in Sicily are most important and have gained recognition in the industry. These are: the "*District of the Sicilian ceramics*" and the "*District of the ceramics of Caltagirone*". In particular the *District of the ceramics of Caltagirone* is one of the most best ceramics district not only at regional and Italian level but also at international level. Caltagirone has been renowned since ancient times for its excellent and pleasant ceramics, for the elegance of its traditional design and for the creativity of its craftsmen. It is a small industrial district with almost 150 workers working in fewer than 90 very small enterprises located in the territory of the city of Caltagirone. Two enterprises located in the province of Messina (Patti e Taormina) and one in the province of Palermo (Monreale). The enterprises working in the sector base their activities on the last two phases of the production chain: the processing of the "raw product" (called "verde") and its decoration. Among these two phases, the last one has higher economic relevance. This is because most of the "raw material" used by the artisan comes from national (Deruta, Faenza, Vicenza) or regional (Santo Stefano di Camastra) ceramics districts. Nowadays, however, few artisans have begun producing "raw material" in the territory of Caltagirone.

Caltagirone ceramics have been used for centuries to decorate houses, public and private parks, churches, streets and squares. Nowadays, besides the traditional and lively production of ceramics, both functional and decorative, Caltagirone is also famous for the ceramic whistles and the Presepi, nativity scenes made with terracotta or ceramic characters and accessories. which carefully revive the daily life of simple people over the centuries. One of the most common art craft, accounting at times for almost 50% of the entire production of an enterprise, is the ceramic plate which can have both domestic and ornamental purpose.

3 METHODOLOGY

Life Cycle Assessment (LCA) methodology represents a very powerful tool in Industrial Ecology useful for estimating and assessing the environmental impacts attributable to the life cycle of a product/service (for example climate change, eutrophication, acidification, resources depletion, water or land use). The methodology, following the requirements of the ISO standards 14040 and 14044: 2006 is made up of four phases:

1. Goal and scope definition, which provides description of the purpose of the study, expected product object of the study, system boundaries, Functional Unit (FU) and all assumptions done;
2. Life cycle inventory (LCI) analysis, which is the phase where an estimation of the consumption of resources and of the quantities of waste flows and emissions caused by or otherwise attributable to a product's life cycle is done; The inventory results are presented in complete input-output tables that quantify inputs and outputs like raw materials, water consumption, electricity, emissions to air, soil, water and solid waste generation [10], [11]. By doing so, it is possible to realise the evaluation of the environmental loads associated with the life cycle of a product by the analysis of the true consumption of energy, the consumption of the natural capital and the emissions to the environment [12]. Representative life cycle inventories are essential for any good quality LCA study because they represent fundamental building blocks for its compilation. This LCI represents the starting point for the whole LCA and can be the basis for future decisions about the environmentally friendly management of the production of ceramics.
3. Life cycle impact assessment (LCIA), which is carried out on the basis of the inventory analysis data It provides indicators and the basis for analysing the potential contributions of the resource extractions and wastes/emissions in an inventory to a number of potential impacts;
4. Life cycle interpretation (LCI), in which the results from the impact assessment and the inventory analysis are

analyzed and conclusions are established in a way that is consistent with the goal and scope of the study.

Among the four phases, the most important one is the LCI because it allows the building of an analogue model of reality, representing, as close as possible, all the exchanges among the single actions belongings to the effective production chain.

This paper deals with only the first two steps of the LCA methodology, the goal definition and scoping phase and the inventory analysis one, with the aim of developing the LCI of decorative ceramic plates.

3.1 Goal definition and scoping

The purpose of this paper is to investigate the life cycle inventory of ornamental ceramic plates (variable diameter) during their life cycle and to identify the "input and output material and energy flow" inventories associated with their production. Decorative ceramic plates represent one of the most common and typical production of the ceramics of Caltagirone: they can be used both for domestic and ornamental purpose.

3.2 Functional Unit (FU)

The purpose of the Functional Unit (FU) is to provide a reference unit for which the inventory data are normalized. In order to calculate the material and energy flow, 1 kg of decorative ceramic plates of different diameter was chosen as the FU.

3.3 System boundaries

The system boundaries defined include the following phases: manufacturing of the plates; end of life of the plates; and transportation of the plates to the landfill. Details of the production system studied are shown in the process flow diagram in Figure 1, from which it can be possible to deduce how processes of the product system are interconnected through commodity flows.

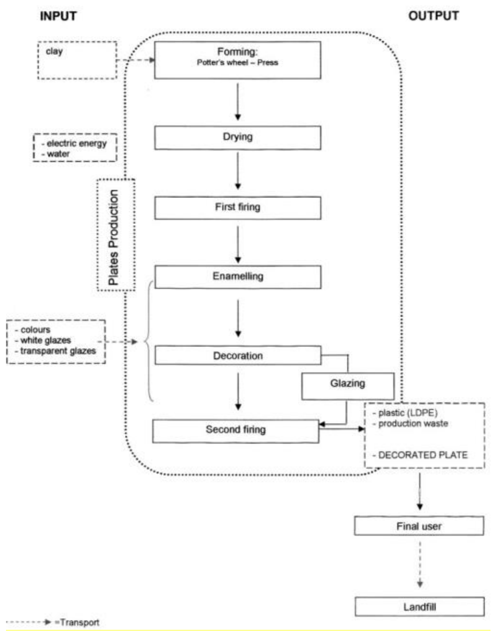


Figure 1: System boundaries.

It has to be highlighted that the use phase of the plates by the final user was excluded from the system boundaries and, with it, also the correlated environmental impacts due, for example, to water, detergents and electrical energy used for their cleaning. This is because, as said before, the examined plates have just ornamental purpose and it is assumed that they are rarely used.

3.4 Inventory analysis and data collection

For realizing the life cycle inventory of the FU it was necessary to represent the entire life cycle of it inside the software used for the analysis. In table 1 the input data related to the ceramic plates life cycle are reported, being referred to the phases: production, end of life and transportation: in particular it has to be noted that the first phase was computed for the share related to the FU.

Table 1: Input data for LCA of 1 kg of ceramic plates.

Functional Unit (FU)	1	kg	Ceramic plates of variable diameter (10 - 90 cm)
Input flow	**Physic amount**	**Measure unit**	**Comment**
Production	1	kg	This phase has been represented creating the "production" life cycle, then computing it for the share associated to the FU
End of life	1	kg	Treatment of the FU at the landfill.
Trasport	50	kg*km	Trasport by the final user of the FU to the landfill

Production phase

Forming (Potter's wheel – Press): the clay undergoes shaping processes and this can be performed manually or with the help of special machines.

Drying: the shaped clay pieces are dried by letting the residual water contained in the clay to evaporate. This phase can be natural or forced (using dryers). Usually the small ceramics enterprises adopt the first method, the industrial ones the second. It is important to pay attention to the drying phase of the clay pieces: they have to dry slowly, especially in the first phase, since the quantity of water contained in the pieces is still excessive. In fact, if the drying occurs rapidly at this stage, distortions, cracks and detachment of parts added (as handles or other elements) can occur.

First firing ("ceramic bisque" firing): bisque firing is the first firing, and sometimes is also the last firing, if no transparent glaze is added. Firing is necessary in order to transform the clay so that it will no longer "melt" if left in water. The "bisque" is ceramics which has been fired once, without glaze, to a temperature just before vitrification. This stage is carried out at a temperature between 900 - 950°C using wood, gases, gasoline, kerosene, coke, electric kilns. Recently experiments applying solar energy for alimenting the kilns have been done.

Enamelling: after the first firing, the bisque is dipped into a bath of fast drying liquid white glaze. When dry, the glazed piece is ready to be hand painted. The ceramics of Caltagirone is renowned for its use of enamels which, when applied to terracotta, give origin to majolica. The most commonly used enamel is white, lustrous, matt for the tin oxide and it is able to form the coating of the majolica. In the tradition of the ceramics of Caltagirone, the enamel is applied on the bisque and it is used for coating the piece that will undergo the decorating stage. The glazing can be carried out, manually, by immersion of the object in an aqueous solution of enamel or brush (on small objects or when you want to give the effect of casting) or by spraying by means of spray gun in a special booth.

Decoration: ceramic crafts decoration is hand made by skilled decorators, using ceramic colours that are made by mixing one or more pigmented oxides with fluxes, plasticizers and hardeners, bearing in mind the chemical properties of the colorant used and its expansion and controlling the operating temperature.

Glazing (optional phase): it consists of the application on the decorated ceramic piece of a transparent glaze for obtaining, after the second firing, a lucid effect.

Second firing: final firing at 920-950°C will make the glaze interact with the metal oxides used by the painter to create the deep and brilliant translucent colours specific to majolica.

As has been clearly described, the production phase includes some stages that provide the use of white glaze (frit), transparent glazes (crystalline) and colours. For each of them, it was necessary to create the relative life cycle data because they do not exist in the software used for the analysis. For each of them 1kg was chosen as the FU and they are presented in tables 2, 3,and 4.

Every process was, then, computed in the life cycle of the ceramic plates for the share related to the FU (Table 5).

The inventory data were collected from various sources, paying attention to data quality and integrity. Most of the data were collected from people working in the sector. Thus, it was possible to measure the quantity of electricity, water, clay, white and transparent glaze and colour used in the production of the ceramic plates. The Ecoinvent database was used for assessing the impact of white and transparent glaze and colour production and also for all the transportation.

Table 2: Input data for 1kg of white glaze production.

Functional Unit (FU)	1	kg	White glaze (frit)
Input flow	**Physical amount**	**Measure unit**	**Comment**
Resources			
Water process, well in ground	0.404	kg	Amount of water for the production of 1 kg of white glaze used for enamelling
Raw materias and fossil fuels			
Zinc oxide, at plant/RER S	0.073	kg	
Zirconuim oxide, at plant/AU S	0.0317	kg	
Dolomite, at plant)	0,157	kg	
Aluminium oxide, at plant/RER S	0.067	kg	
Titanium dioxide, production mix, at plant/RER S	0.00192	kg	
Feldspar, at plant/RER S	0.213	kg	
Calcium borates, at plant/TR S	0.125	kg	
Sodium perborate, tetrahydrate, powder, at plant/RER S	0.106	kg	
Silica sand, at plant/DE S	0,241	kg	
Barite, at plant/RER S	0.00962	kg	
Tin, at regional storage/RER S	0.000962	kg	
Lead, at regional storage/RER S	0.124	kg	
Electric and thermal energy			
Electricity LV use in I + import S	0.16	kWh	Amount of electrical energy for white glaze production
Transport, lorry 7.5-16t, EURO5/RER S	57.5	kg*km	Raw materials transport to the company producing the white glaze (Montelupo Fiorentino - ITALY). Average distance 50 km for a total of 1,15 kg of raw material

Table 3: Input data for 1kg of transparent glaze production.

Functional Unit (FU)	1	kg	Transparent glaze
Input flow	**Physical amount**	**Measure unit**	**Comment**
Raw materias and fossil fuels			
Production 1 kg frit	0.956	kg	95% of transparent glaze is made of frit
Kaolin, at plant/RER S	0.04	kg	
Cobalt, at plant/GLO S	0.001	kg	
Sodium chloride, powder, at plant/RER S	0.03	kg	
Electric and thermal energy			
Electricity LV use in I + import S	0.16	kWh	Amount of electrical energy for the transparent glaze
Transport, lorry 3.5-7.5t, EURO5/RER S	3.3	kg*km	Raw materials transport to the company producing the crystalline (Montelupo Fiorentino – ITALY). Average distance = 75 km

Table 4: Input data for 1kg of colour production.

Functional Unit	1	kg	Colour
Input flow	**Physical amount**	**Measure unit**	**Comment**
Raw materias and fossil fuels			
Production 1 kg transparent glaze	0.91	kg	
Zinc oxide, at plant/RER S	0.00405	kg	
Zirconuim oxide, at plant/AU S	0.00115		
Aluminium oxide, at plant/RER S	0.003		
Titanium dioxide, production mix, at plant/RER S	0.0001		
Lime B250	0.00455		
Magnesium oxide, at plant/RER S	0.0003		
Boric oxide, at plant/GLO S	0.0057		
Potassium chloride, as K2O, at regional storehouse/RER S	0.00065		
Silica sand, at plant/DE S	0.021		
Barite, at plant/RER S	0.00055		
Tin, at regional storage/RER S	0.0001		
Lead, at regional storage/RER S	0.0069		
Soda, powder, at plant/RER S	0.00195	kg	
Kaolin, at plant/RER S	0.01	kg	
Zirconuim oxide, at plant/AU S	0.01		
Boric oxide, at plant/GLO S	0.02		
Electric and thermal energy			
Transport, lorry 7.5-16t, EURO5/RER S	1500	kg*km	Colour transport from the company producing it (Montelupo Fiorentino – ITALY) to the ceramics company (SICILY, d= 1500 km)
Transport, lorry 3.5-7.5t, EURO5/RER S	4.5	kg*km	Raw materials transport to the company producing the colour (Montelupo Fiorentino – ITALY). Average distance = 75 km

Table 5: Input data 1 kg ceramic plates production

Functional Unit (FU)	1	kg	Ceramics plates of variable diameterse (10 - 90 cm)
Input flow	**Physical amount**	**Measure unit**	**Comment**
Resources			
Water process, well in ground	4	kg	Amount obtained comparing the total used amount of water ($40 m^3$ of water for 12000 kg of clay) to 1.2 kg of clay used for the FU
Raw materias and fossil fuels			
Clay, at mine/CH S	1.2	kg	Amount of clay for 1 kg of plates (taking into account a weight loss of 20%)
Production 1 kg white glaze	0.0521	kg	Amount of glaze, computing it for the share associated to the FU.
Production 1 kg di colour	0.0104	kg	Colour, computing it for the share associated to the FU
Production1 kg di transparent glaze	0.00521	kg	Crystalline, computing it for the share associated to the FU. (its use is optional)
Electric and thermal energy			
Electricity LV use in I + import	1.73	KWh	Amount obtained comparing the total used amount of electric energy (17.3 MWh of electric energy for 12000 kg of clay) to 1.2 kg of clay used for the FU
Transport, lorry 3.5-7.5t, EURO 5	78.15	kg*km	Transport of the white glaze form supplier (Montelupo Fiorentino – ITALY) to ceramics company (SICILY, d = 1500 km)
Transport, lorry 3.5-7.5t, EURO 4	7.815	kg*km	Transport of transparent glaze form supplier (Montelupo Fiorentino – ITALY) to ceramics company (SICILY, d = 1500 km)

4 DISCUSSION

The aim of this paper was to realise the LCIA of decorative ceramic plates (variable diameter) and to identify the material and energy flow inventories associated with their production. This allows the identification of all the raw materials and the energetic resources linked to the ceramics plates' life cycle, facilitating the quantification of the resources which is necessary for the next LCA steps: the Life Cycle Impacts Assessment and the Life Cycle Interpretation phases.

The study results show that for among the three phases taken into account in the system boundaries (manufacturing, end of life and transportation of the ceramics plates), the most inventories are in the manufacturing phase (for more than 90% of the total damage). There is a huge amount of electrical energy used during the manufacturing of the ceramics plates: this is because the first and the second firing occur in an electrical kiln at very high temperatures. On the contrary, the raw materials, glazes, colours is almost negligible.

5 CONCLUSION

As stated at the beginning of this paper, the Sicilian artistic and traditional ceramic production (and so the ceramic art craft) can be seen as a medium for enhancing the local production, the culture and the territory related to it. The industry is economic and productive and also has historical and artistic value. It is an industry in crisis and the difficulties that the sector is going trough are the ones typical of sectors characterised by a low technological and organizational level, such as, for example, few opportunities of experimenting new materials and new manufacturing/firing techniques or scarce orientation to activities with a higher environmental sustainability level (for example, the use of renewable energy or eco-friendly materials). A good way for overcoming this crisis and enhancing the ceramics production could be by focusing on high quality, innovation and sustainability of the manufacturing process, respecting, at the same time, the tradition of the cultural productive processes. This could be achieved by obtained looking for new and more sustainable material and technologies or by finding new ways for recycling the waste from the production processes.

As highlighted in the last paragraph, the most of the inventory occurring during the life cycle of the ceramic plates is due to the large amount of electrical energy consumed by the kiln used for the manufacturing of the ceramics plates. Kilns are an essential part of the manufacturing of all ceramics, since they require heat treatment, often at high temperatures: during this process, chemical and physical reactions occur that permanently alter the clay. In this context, one possible improvement could be trying to reduce the amount of energy used for the firing stage and finding more sustainable ways of feeding the kiln. This could be obtained using, for example, kilns supplemented by solar energy or gas, such as methane. A second improvement could be the possibility of using recycled raw materials.

Future work needs to conduct a full assessment and to provide further interpretation of the results obtained. Furthermore, even if the developed topic is very specific the papers helps to show what the possible applications of the methodology are. The LCI structure and the results can be usable in case studies among the ceramic sector focusing other items.

6 REFERENCES

[1] Assopiastrelle, 2013. http://www.assopiastrelle.it/cti%5Carticoli.nsf/VSNWA1/C6D6A24BD374C092C1256AC6004BE179. Accessed 12 January 2013

[2] Nicoletti, G.-M., Notarnicola, B., Tassielli, G., 2002, Comparative life cycle assessment of flooring materials: ceramic versus marble tiles, J. of Cleaner Production, 10:283-296.

[3] Bovea, M.-D., Diaz-Albo, E., Gallardo, A., Colomer, F.-J., Serrano, J., 2010, Environmental performance of ceramic tile: improvement proposals, Materials and Design, 31:35-41.

[4] Bovea, M.-D., Serrano, J., Bruscas, G.-M., Gallardo, A., 2006, Application of Life Cycle Assessment to improve the environmental performance of a ceramic tile packaging system, Packag. Technol. Sci., 19:83-95.

[5] Bovea, M.-D., Saura, U., Ferrero, J.-L., Giner J., 2007, Cradle – to Gate study of red clay for use in the ceramic industry, Int J LCA, 12/6:439-447.

[6] Breedveld, L., Timellini, G., Casoni, G., Fregni, A., Busani, G., 2007, Eco-efficiency of fabric filters in the Italian ceramic tile industry, J. of Cleaner Production, 15:86-93.

[7] Mahalle, L., 2010, A comparative Life Cycle Assessment of Canadian hardwood flooring with alternative flooring types, Energy & Environmental Group Building System Department Wood Products Division, Project n. 201002354.

[8] Almeida, M., Dias, A.-C., Castanheira, E., Arroja, L., 2011, Environmental product declaration in ceramic materials as sustainability tool, Proceeding of "LCM 2011, Towards Life Cycle Sustainability Management", 28-31 august 2011, Berlin, Germany, 1-10.

[9] Calamandrei, D., Fiasconaro, M., 2008, La ceramica artistica e tradizionale in Italia. Quadro di sistesi, prospettive e fattori di successo, First national conference on artistic ceramics, 08 october 2008, Roma.

[10] Fawer, M., Concannon, M., Rieber, W., 1999. Life Cycle Inventories for the Production of Sodium Silicates. Int. J. LCA 4/4: 207-212.

[11] Suh S., Huppes, G., 2005. Methods for Life Cycle Inventory of a product. Journal of Cleaner Production 13:687-697.

[12] Lo Giudice, A., Mbohwa, C., 2012. Life Cycle Inventory analysis of citrus fruit in Sicily in Proceedings of the conference IADIS International Conference on "Sustainability, Technology and Education 2012", 28 – 30 November 2012, Perth, Australia, 101-108.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

6.3 Structured identification of business improvement opportunities using Life Cycle Assessment: A case study in the gas turbine industry

P. Martínez-Caballero [1], B. Basdere [1], J. Richter [1], F. Parthey [2], K. Mueller [2]

[1] Turbine Airfoil Coating and Repair GmbH, Berlin, Germany

[2] Siemens AG, Berlin, Germany

Abstract

In the last two decades the power sector has been adopting environmental conscious practices in several business areas and processes. Bridging the identification of environmental “hot-spots” in the product life cycle and the implementation and execution of an environmental management system requires an integrated approach starting with a Life Cycle Assessment to identify the improvement potentials; then analyzing the current management and product development systematics in use, and finally mapping the environmental practices against the improvement potential. The improvement tracking will be embedded in the management system as an Environmental Improvement Roadmap, mapping the efforts required to realize the goals. The methodology has been implemented in pilot studies, focusing on the processes performed in-house to enable further decisions on process alternatives and providing reliable information for strategic decisions within the Siemens Environmental Product Portfolio.

.

Keywords:

Life Cycle Assessment; Eco Design, Environmental Portfolio

1 INTRODUCTION

In the last two decades the industrial sector has been going through an increasing “green” period, in which all industry players have been adopting environmentally friendly practices in several business areas and processes. Companies produce goods and services that require inputs of energy and raw materials. These goods and services in turn serve as inputs for the production of other products, hence interconnecting a complex network of suppliers and customers, all of them consuming resources and disposing waste and emissions to the environment. It is therefore necessary to redesign the industrial systems to create more value with fewer resources, without compromising sustainability.

2 STATE OF THE ART

During the Earth Summit conference in Rio de Janeiro in 1992, a number of agreements were produced and 27 basic principles of sustainability were deduced [1]. Despite the valuable message of these principles, some criticize that there is a high moral claim in the definition, but a lack of guidance on how this aim can be reached [2]. Transferring the sustainability principles to operational and technical goals is not always easy because there is little awareness and understanding of the wider environmental, social and economic impacts among product development teams and the operational departments of an organization [3]. It has been stressed that in order to identify and produce significant improvements in a company’s environmental performance, there is a need for integrated business processes that bring together all of the principles, practices and methodologies [1] in order to operationalize environmental and sustainable development [4].

Seen from a company’s perspective, the above described situation can be summarized in the following four questions: 1) what to improve? 2) how much to improve? 3) when to improve? and 4) how to improve?. By means of performing a literature review, it has been observed that questions 1) what to improve? and 4) how to improve? have been extensively studied by the academia and the industry. On the one hand, researchers aiming to answer the question: what to improve? have found the answer by focusing in the product and everything around its development process and production system. On the other hand, the question: how to improve? has been answered by focusing in the Environmental Management Systems (EMS) of the companies and the supply chains. In both cases a relatively large amount of research has focused on how to make environmental impacts a measurable variable, and consequently, a vast number of frameworks, methodologies, systems and tools have been developed so the industry is able to assess and control these impacts. A central methodology for identifying environmental impacts of products is the Life Cycle Assessment, which will be explained and employed later on.

In contrast, questions 3) how much to improve? and 4) when to improve? have not received as much attention from the researchers as needed, at least not in an operational level. These questions make reference to the definition of the goal and scope of the environmental improvement efforts; that is an environmental strategy. The strategic component between

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

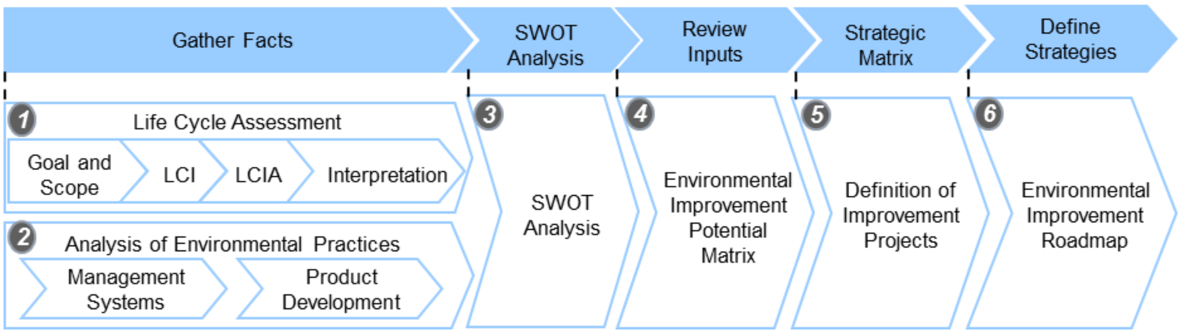


Figure 1: Methodology Definition

the identification of environmental "hot-spots" and the implementation and execution of an Environmental Management System (EMS) has been identified as a gap in the process of identifying environmental improvement opportunities.

3 METHODOLOGY DEFINITION

In order to bridge this strategic gap, and with the purpose of defining the goal and scope of an environmental improvement plan, a methodology based on the current industrial practices and developments has been compiled and defined. The approach, which can be seen in Figure 1, comprises the strategic environmental planning and starts with the development of a Life Cycle Assessment (LCA) to identify the environmental improvement potential. Then, it analyses the management and product development systems currently implemented within the organization. By combining the results of the last two steps, an analysis of the organization's strengths, weaknesses, opportunities and threats (SWOT Analysis) in the context of environmental practices is performed. By using a so called environmental improvement potential matrix, the organization's current position is mapped against the product improvement potential and the required management effort to realize it. This tool supports the definition of improvement projects and leads to the creation of an environmental improvement roadmap, describing the actions required for achieving an environmental target within a defined time span.

With the purpose of implementing the Strategic Environmental Planning and proving its efficacy and effectiveness in the identification of improvement opportunities, the methodology has been applied in a case study in the power generation sector. The outcomes have been analyzed and discussed in relation to the objectives and its possible applicability in different organizations and industries.

4 CASE STUDY

The scope of the case study covers a state-of-the-art combined cycle power plant as part of the Siemens Environmental Portfolio. Obtaining the environmental footprint of all components all the way down to a single turbine blade or vane is of particular interest due to the important role in the turbine operation and its specific design and manufacturing characteristics, such as: the highly advanced alloys from which these components are casted; the specific casting processes that have to be carried out; the accuracy and precision of the machining processes due to the limiting dimension tolerances; and the corrosion resistant- and thermal barrier coatings that are applied. All these processes are energy-intensive and use specific materials and machinery of large value and specificity, which besides influencing the costs of the blade, might also influence the product's impact on the environment.

5 LIFE CYCLE ASSESSMENT

A full scale Life Cycle Assessment has been carried out according to the ISO 14040 standard and contains the following four components: (1) Goal and Scope definition, (2) Life Cycle Inventory, (3) Life Cycle Impact Assessment and (4) Interpretation.

5.1 Goal and Scope Definition

The LCA study had the following goals:

1. Identification and comparison of the dominating causes of environmental impacts along the supply chain.
2. Identification and comparison of different process alternatives.
3. Comparison between the life cycles of the Tla1 and Tla2 blade types.
4. Comparison of several life cycle scenarios with a different number of refurbishment (service) processes carried out after an operation phase.

Functional Unit:

The LCA focuses on the first and second stage blades of the SGT5 4000F gas turbine, named Tla1 and Tla2 respectively (see Figure 2). These blades have to withstand the largest loads and stresses, in mechanical, chemical and thermal terms; meaning that they wear faster and therefore have shorter operation life cycles. Consequently, these blades are refurbished one or more times after an operation phase (other blades and vanes might not need refurbishment),

Tla1 Tla2

Figure 2: Blade types

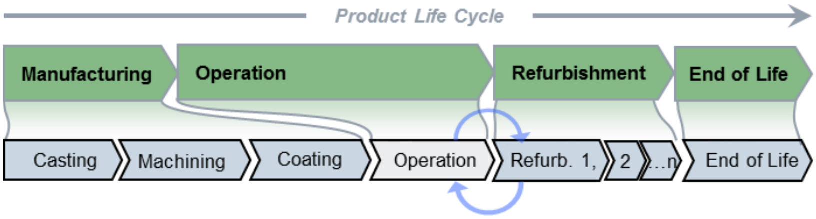


Figure 3: Modeled Life Cycle

which adds the "service" phase to the product life-cycle; hence enriching the system under study and the scope of the analysis. The functional unit of the LCA is therefore one (1) blade of the corresponding blade type (Tla1 and Tla2) fulfilling its operating function within the turbine.

Examined Life Cycle

Each single blade, independent of its type, has a different life cycle and life span depending on its use and damage during operation within the turbine. Nonetheless, since there is a finite number of fundamentally equal life cycle phases, a generic life cycle (shown in Figure 3) composed by the following four main phases can be defined.

1. Manufacturing: It is comprised by the following stages, each performed by a different company.
   a. Casting: The blades are casted out of a special Nickel-alloy into the blade shape using an investment casting process
   b. Machining: The blade foot is grinded and milled to obtain its final shape and surface finish
   c. Coating: The blade is coated with a corrosive resistant layer and a ceramic thermal barrier
2. Operation: During the operation of the turbine, and hence the power plant, the blade plays the role of a passive component of a greater product or system, whose operation characteristics are dependent of several other components, and therefore not attributable or allocable to the blades. The reason why this phase is part of the life cycle is because the operating lifetime of the blade is of importance.
3. Refurbishment (Service): Depending on its condition, the blade is either repaired and coated again to later go back to operation; or it is designated as waste. Therefore this phase could or could not take place during a life cycle.
4. End of Life: The blades that cannot be repaired are disposed following a waste treatment process that includes recycling.

System Boundaries:

The system boundaries, illustrated in Figure 4, were selected based on the study objectives and to be compatible with the defined functional unit and with the turbine and power plant system boundaries. The following observations are important to recognize:

- The system boundaries are valid for both Tla1 and Tla2 blades.
- The operation phase is outside the system boundaries and therefore no inputs and outputs have been considered. The transportation to and from the operation site is however included
- All the inputs and outputs have been modeled using information from databases, and not as additional processes or systems.

5.2 Life Cycle Inventory

The collection of the data has been performed in six different sections. This classification has been rather based on the supply chain structure than on the product life cycle.

1. Production Step: Casting
2. Production Step: Machining
3. Production Step: Coating
4. Life Cycle Phase: Refurbishment
5. Life Cycle Phase: Operation (only transport)
6. Life Cycle Phase: End-of-life

All process data and the inventory have been modeled with SimaPro software and using the Ecoinvent Database.

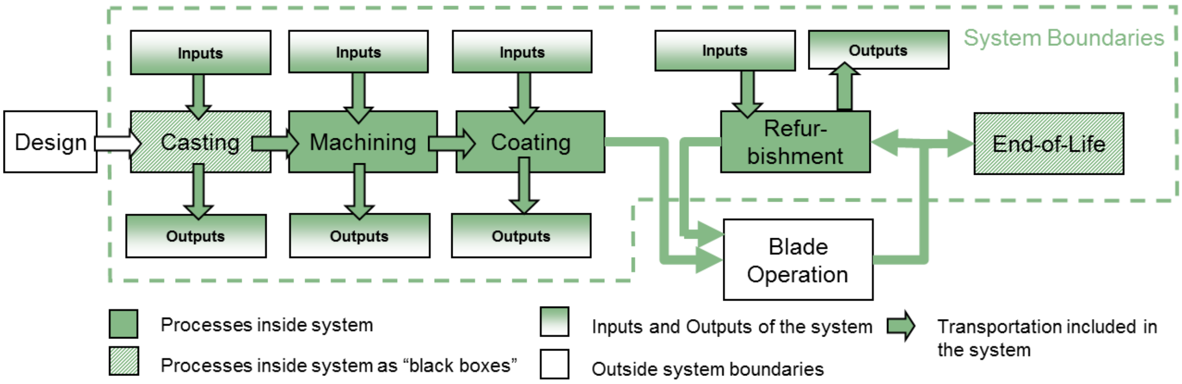


Figure 4: System Boundaries

5.3 Life Cycle Impact Assessment

Impact categories

A comprehensive set of impact categories has been analyzed to identify all hot spots and trade offs of the product life cycle. However the Global Warming Potential impact category, measured in CO_2e equivalent units (CO_2e) has been selected for further communication and comparisons.

For blade types TIa1 and TIa2 there is an average life cycle that represents the normal life path that a blade of these types undergoes, based on its wear propensity and its reparability. In average, these blades can be repaired and consequently be submitted to several operating cycles.

6 IDENTIFICATION OF IMPROVEMENT OPPORTUNITIES

6.1 Environmental Improvement Potential Matrix

Based on the environmental management system and product development status of the analyzed organization and a following SWOT analysis, the improvement potential matrix has been prepared. The descriptions of the current position and the improvement potential are the following:

Current Position

Management level:

- The Environmental Management System (EMS) is an ISO conforming and certified system
- The EMS focuses on the operational aspects of the environmental management
- The EMS is implemented locally within the company organization.
- The planning is based on a strategic target

Product level:

- Manufacturing is not the owner of the blade design
- The Technology department interacts with the design owner to develop and certify the processes

Improvement potential

Management level:

- The current EMS has the potential to grow and become a fully integrated system within the organization functions
- The proactive engagement of the top management in the planning of supply-chain targeted projects can lead to an increased reduction of the environmental footprint

Product level:

- The services provided by the organization have the potential to be improved in the short- and mid-terms, and redesigned in the long term.
- Innovation of the coating services

6.2 Definition of Improvement Projects

In order to reach the improvement potential plotted in the Environmental Potential Matrix and based on the SWOT Analysis, a list of 15 projects with defined improvement potential has been created. The input information for deriving the list of projects includes the results of the LCA and further methodology steps, as well as ideas developed during the development of the LCA due to empirical observations and information exchange with employees.

6.3 Environmental Improvement Roadmap

Figure 5 shows the resulting Environmental Improvement Roadmap comprising the suggested projects in order of implementation and related by means of predecessor and sequence connectors. The roadmap has two vertical axes for the two stages of the blades. While the primary axis is scaled in proportion to the target value, the secondary axis is not

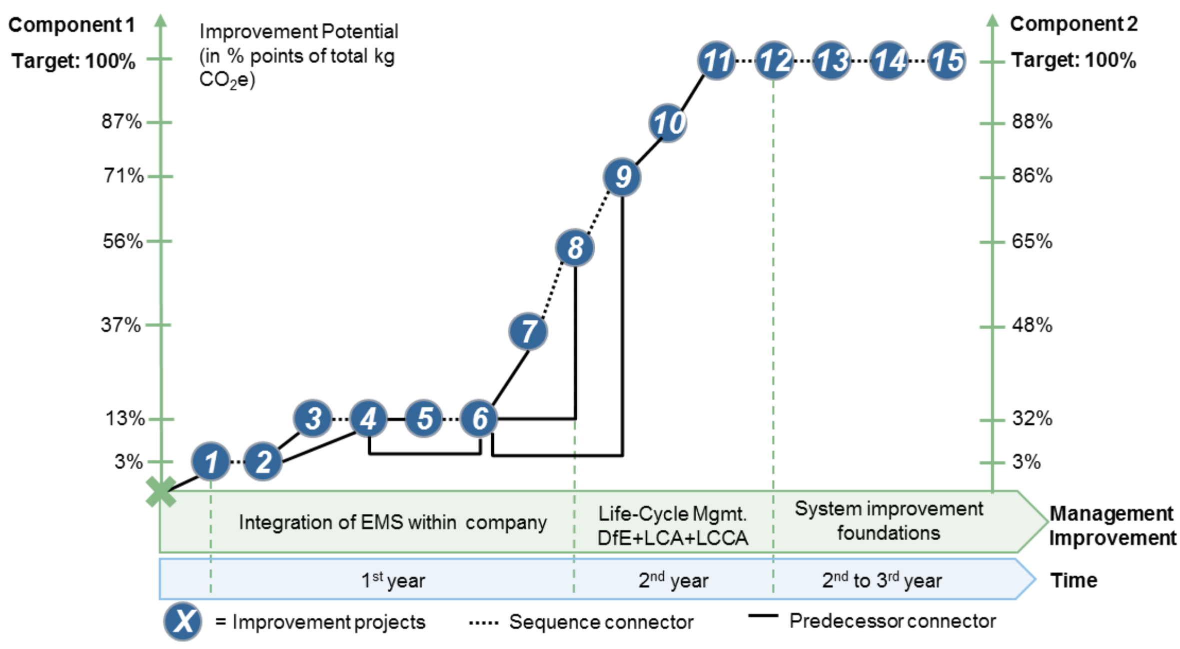


Figure 5: Environmental Improvement Roadmap

However, the labeled values match the real increments of the respective projects for both blade types. The Management Improvement horizontal axis is descriptive, and therefore arbitrarily labeled according to the characteristics of the improvement curve shaped by the project implementation sequence, as well as to each project characteristic. The Time horizontal axis is also descriptive and the time periods were defined considering each project's implementation duration and the natural business planning and execution cycles.

7 CONCLUSIONS

- The identified improvement potential represents a direct reduction of the carbon footprint of the respective components
- The application of the Strategic Environmental Planning methodology increased the strategic planning time-span
- to three years (long-term perspective) and considered the expansion of the EMS to other functional areas of the company (systems perspective); therefore the identified potential and target resulted significantly larger than the current annually planned improvement.
- The methodology does not consider economic aspects; however these can be integrated by using trade-off analysis tools or project portfolio techniques.
- The Strategic Environmental Planning methodology clearly fulfills its objective of defining the scope and goal of an environmental plan.

8 REFERENCES

[1] Fiksel, J.R., 2009. Design for Environment: A Guide to Sustainable Product Development, McGraw-Hill.

[2] Klöpffer, W., 2003. Life-Cycle based methods for sustainable product development. The International Journal of Life Cycle Assessment, 8/3:157–159.

[3] Howarth, G., Hadfield, M., 2006. A sustainable product design model. Materials Design, 27/10:1128–1133.

[4] Seuring, S., 2004. Emerging issues in life-cycle management. Greener Management International, 45/Spring 2004:3–8.

9 DISCLAIMER

11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

6.4 Integrating Life Cycle Assessment tools and information with Product Life Cycle Management / Product Data Management

A. Ciroth [1], J.P.-Theret[2], M. Fliegner[3], M. Srocka[1], V. Bläsig[3], Ö. Duyan[1]

[1] GreenDelta GmbH, Berlin, Germany

[2] Dassault Systèmes, Meudon La Foret, France

[3] Pernexas AG, Munich, Germany

Abstract

Integrating Product Data Management (PDM) solutions with Life Cycle Assessment (LCA) software offers the opportunity to obtain LCA results fast, based on high-quality, product-specific information and integrated into the design workflow, enabling thereby, inter alia, efficient Design for Environment (DfE).

In a recent project, Dassault Systèmes and GreenDelta have investigated different options for combining LCA tools and information with the ENOVIA platform, a broadly used PDM and Product Life Cycle Management (PLM) platform by Dassault Systèmes. In the course of the project, solutions have been developed for main LCA software systems, including SimaPro, GaBi, EIME, and openLCA. A demonstration implementation has been performed for the openLCA software. A specific connector interface, called 'eLCA', was developed in the project; it provides an interface which makes it easy for LCA software to "dock" to eLCA that in turn links to the ENOVIA platform. The paper will describe the technical solution that has been developed and show its benefit and further potential.

Keywords:
Bill of Material, Computer Aided Design, Life Cycle Assessment, Design for Environment, Product Data Management, Product Lifecycle Management

1 INTRODUCTION

Product data management (PDM) systems have been integrated within product life cycle management (PLM) especially for the design of complex products which allows companies to find correct data quickly, improve productivity and collaborate between global teams as well as to adapt product legislations. Environmental regulations and customer expectations enforce companies increasingly to also consider the environmental impact of products during design and manufacturing processes. Making right decisions in production and design stages requires a combination of product information and impact data. Material choices and manufacturing processes evidently have a high influence on the environmental impact of a product. Further, it is difficult to change those choices after a product has been designed. Late product changes can increase costs. Therefore, well-informed decision making at early product design stages becomes important. Life Cycle Assessment (LCA) is the accepted approach for providing comprehensive information on environmental impacts of a product. The information from LCA study should be consistent within the realm of decision making for different perspectives within product development process such as product designer, production and product managers. Especially for product managers, LCA can have positive affect on decision making if it is provided in operative routines; thus, performing an LCA study based on a real time Bill of Material (BOM) or Bill of Process (BOP) seems ideal for good decision support. However, collection of data for the product life cycle inventory can be expensive and time consuming. At the same time, a very large share of the required data is available in the PDM system.

2 LINKING PDM/PLM AND LCA

An approach to obtain LCA relevant information from the PDM system can be to export BOM or BOP in an LCA format (EcoSpold or ILCD) and import this into the LCA software; likewise, calculated results from the LCA software can be exported in an LCA exchange format and imported back again into the PDM/PLM software. This import and export allows information exchange but is of course not very interactive. For this reason, development of a connector which supports the connection of LCA tools to PDM software helps designers and manufacturers to perform LCA studies more easily. In the project, such a connector software was developed, called eLCA.

2.1 eLCA Connector software principles

eLCA Connector is a software developed to support a connection between the ENOVIA platform and LCA tools; aim is to calculate reliable LCA cases based on information available in ENOVIA platform, using LCA background data and LCA Impact Assessment models from the LCA software. The interface eLCAis openly documented and invites LCA software providers to link to it. As a demonstration and guidance, a full implementation in the project was created in the project for the openLCA LCA software [4], linking thereby openLCA and ENOVIA. OpenLCA is an open source LCA software and therefore the code can be inspected for illustration and documentation purposes. Investigation of the use for other LCA tools such as SimaPro,GaBi and Eime is also discussed later in this paper.

2.2 Using the eLCA Connector

Required data available in the PDM system can be accessed via the eLCA Connector. An LCA tool for that links to eLCA needs to provide an API or service interface, with the following functions:

- Provide a list of available product systems / processes, Life Cycle Impact Assessment (LCIA) methods, dimensions, units for dimensions
- Return the functional unit of a product system

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

- Calculate a product system using, optionally, an LCIA method that returns a set of LCIA results, scaled to a given functional unit

These design requirements can be implemented in two different ways: Either, a direct Java API can be created that the LCA tool implements, referring to the eLCA Java API (fig. 1), or by RESTful web services whereas the LCA tool provides the eLCA web service protocol (fig. 2).

Figure 1: Direct Java API

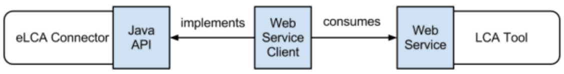


Figure 2: RESTful Web Services

The eLCA Connector is in a first step developed to be connector between openLCA and Enovia PDM software. For the connection to openLCA, the eLCA Connector currently uses an API that directly uses the functions of openLCA (fig 3).

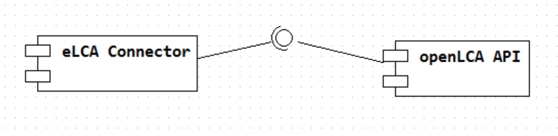


Figure 3: eLCA Connector with openLCA

To enable the use of other tools, this openLCA-specific API is replaced by a general Java API that defines all types and functions that should be provided by an LCA tool to be used in the eLCA Connector (com.elca.api). With this API it is easily possible to replace one LCA tool with another, provided that both tools implement this API. For openLCA a component is under way that provides an implementation of this API with openLCA functions (com.elca.openlca). Fig. 4 shows the structure of these components.

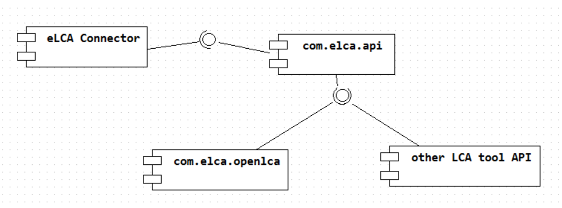


Figure 4: eLCA Connector with other LCA tool Java API

The eLCA Connector is only dependent from the general API which then is implemented by the respective LCA tool.

For a web based LCA software, a component is provided that consumes a RESTful web service and implements this API (com.elca.service.client). Fig. 5 shows the principle of this concept.

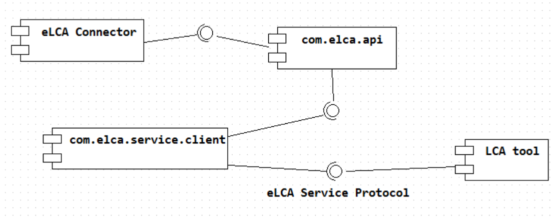


Figure 5: eLCA Connector with other LCA tool web service

The client API implements the general API described above and consumes a web service of a LCA tool that provides the eLCA service protocol.

Such a service is an independent platform and can be implemented in the language of the respective tool provider. It also allows a connection to the LCA tool via the network which in turn makes it possible to run the LCA tool in another operating system.

3 DEMONSTRATING CASE STUDY

While assembling a car, the environmental impact can be influenced and reduced directly in the engineering phase. The engineer can see and decide the use of more efficient materials directly during the construction. For example: "Does the screw that is used to connect the wheel rim to the axle has a low environmental impact or is there still another screw available with the same properties but with a much better environmental impact result?" To provide this information directly during the construction phase, the PDM system on which the engineer works can be extended with the eLCA Connector. The information is provided directly at, for example, the properties page of the screw like any other information. The LCA calculation is fully embedded in the work flow, and there is no need for the engineer to use any other tool than the PDM. The LCA tool can provide information about other parts of the life cycle that are related to the specific part that is currently designed, such as transport and waste management efforts. Of course, it is also possible to "assemble" the life cycle of a complex product based on information of parts of the product.

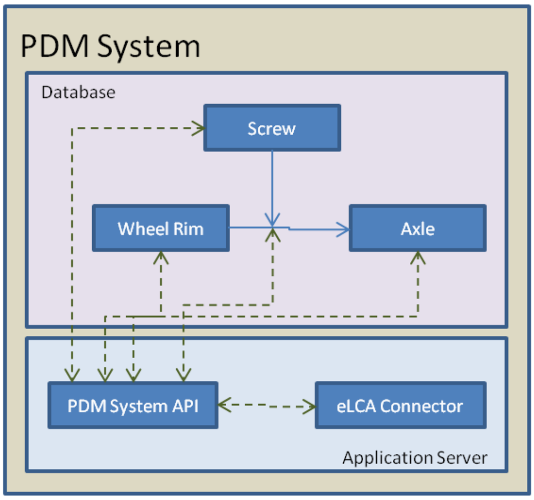


Figure 6: Structure of the case study, as linkages between database, PDM API, and eLCA Connector

4 INVESTIGATION OF OTHER LCA TOOLS

4.1 SimaPro

SimaPro is developed by PRé. It is a Windows desktop software and provides a COM interface which allows the use of SimaPro from other applications. The principle shown in fig. 7 and 8 is to implement a general Java API to call the respective COM functions of SimaPro.

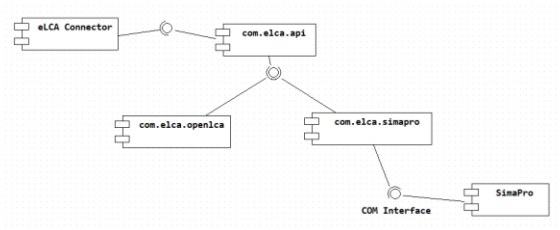


Figure 7: A connection solution for SimaPro, part 1

To use SimaPro via a web-based service in the eLCA Connector, a web-service wrapper prototype is developed which implements the eLCA service protocol.

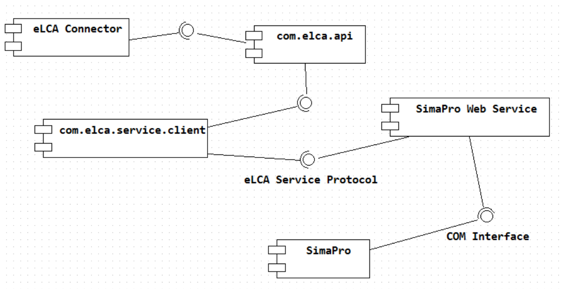


Figure 8: A connection solution for SimaPro, part 2: web-based solution

The SimaPro web-service wrapper provides the SimaPro functions using the COM interface. The eLCA service client consumes this web-service and provides the function of the eLCA Java API which is referenced by the eLCA Connector.

4.2 GaBi

GaBi [5] is developed by PE International. As SimaPro, GaBi is a Windows desktop software. It is not possible to access Gabi functionalities from other tools since there is no public API or service available. For this reason, two options remain to integrate Gabi into eLCA. Either PE International provides an API or service interface that implements the required functions above, or data can be exported from Gabi to transfer into another tool which supports the required functions. The latter option does not allow a dynamic calculation.

4.3 Eime

Eime [6] is a web-application developed by Bureau Veritas CODDE. It is not possible to access Eime functionalities from other tools as there is no public API or service available, but data can be exported in an Eime-specific format. So a solution can be that Eime developers are providing an API or web service interface, or a data exchange is realized from Eime to another tool which provides these features. These options are very similar to the ones proposed for Gabi.

5 CONCLUSION

Linking PDM systems with professional LCA tools is an effective way to consider and reduce the environmental impact of products already in the design phase. Integrating LCA tools in a PDM software and user interface allows dynamic, real time decision, in line with the current design workflow. This integration can be done by a connector that links the PDM software with LCA tools. This paper analyses main, important LCA tools and proposes two generic options for linking suitable LCA tools with a so called “eLCA Connector”, taking the PDM system ENOVIA as an example. One option implements a specific Java API, the other option specifies and implements a web-service with defined specific protocol. For openLCA and SimaPro, both of these options are possible; for Gabi and Eime, the other two analysed LCA tools, this approach is at present not possible since there are currently no APIs or services for function calls from these tools available. An alternative solution can, therefore, be to export data from these tools and transfer into ENOVIA using a file-based interface, relying on common LCA data exchange formats (EcoSpold, ILCD), losing some interactivity and making the exchange less fluent and flexible.

6 REFERENCES

[1] Boks. C, 2006, The soft side of eco-design, Journal of Cleaner Production Vol. 14, pp. 1346-1356

[2] Brindi. C, Carpanzano. E and Chiodi, 2011, LCA Implementation in Firms Environmental Management System Through Modular Product Life Cycle Descriptions

[3] Dewberry. E, and Goggin. P, 1996, Spaceship eco-design, The Interdisciplinary Journal of Design and Contextual Studies, vol. 5-6, pp. 12-17

[4] Giudice. F, La Rosa. G and Ristano. A, 2006, Product Design for the Environment, A Life Cycle Approach, Taylor & Francis Group, London

[5] www.openlca.org

[6] www.gabi-software.com

[7] www.codde.fr/logiciel-acv.com/

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

6.5 Ecological holistic assessment for production technologies

R. Steinhilper [1], M. Süchting [1], A. Kruse [1]

[1] Chair of Manufacturing and Remanufacturing Technology, Bayreuth University, Germany

Abstract

Treating the natural environment in a responsible manner is becoming a key challenge for manufacturing companies. This challenge also regards the planning, implementation and modernization of production technologies. In this case, a new technology should not only have economic advantages, such as higher productivity or flexibility, but should address ecological aspects as well. Many existing approaches only focus on air pollution, measured in CO_2, and therefore consider only one ecological dimension. So these approaches disregard other effects on the natural environment, such as water and soil pollution. Only through a holistic approach, the influences of a production technology on the environment can be considered completely and comprehensively. The following article describes a holistic ecological assessment approach and illustrates this with an example. This approach enables manufacturing companies to ecologically assess production technologies in a holistic way.

Keywords:
Ecological evaluation, Manufacturing, Production Technology

1 INTRODUCTION

Manufacturing companies are always producing in the conflict between high quality, reasonable time consumption and minimal costs. At least since the 1990s the goal of an environmental friendly production has been added to this conflict of cost, time and quality. Especially because of political and social requirements the customers' demand for green products and processes has increased steadily in the last years.

Manufacturing companies themselves also see the need for action in terms of an environmental friendly production. This fact is demonstrated by a continuing high interest from companies in an integration of climate and environmental objectives into their business strategy through an environmental certification according to ISO 14001 [1]. The still growing number of companies that publish data or join environmental initiatives such as the Carbon Disclosure Project underlines this fact, too [2].

In the first instance many attention has been paid for limiting the global warming and the reduction of greenhouse gases. In science, therefore especially methods for the evaluation and reduction of climate-damaging emissions have been developed. Nowadays other environmental aspects such as the protection of water and soil have to be focused, too. However, many of the developed methods consider only one ecological dimension, neglecting other effects on the natural environment such as water and soil pollution.

2 STATE OF THE SCIENTIFIC KNOWLEDGE AND NEED FOR ACTION

2.1 Relevance of environmental system water

Even though the earth's surface is about 71% of water, only 0.62% of the world's available water is groundwater, and therefore drinking water [3]. While in the less industrialized parts of the world, agriculture accounts for almost 90% of water consumption, in highly industrialized areas the industrial sector is responsible for nearly 50% of water consumption. However, according to the UN World Water Development Report little information is available about how much water is consumed and removed by industry for manufacturing processes [4]. Many of today's manufacturing processes are responsible for contamination affecting the chemical quality of the water, the using and the production of drinking water [5]. Even though statistics show that industry, in the macro view, is not necessarily the worst polluter in terms of concentrations and loads, the effects can be very significant. Industrial contamination tends to be even more concentrated, more toxic and harder to treat than other pollutants [4]. The importance of environmental system water should not be underestimated [6]. The reason why water was not regarded intensively enough in the past could be that ecological assessments were mainly developed in countries without water scarcities [7].

2.2 Relevance of environmental system soil

Soil is a finite, non-renewable resource that is essential for the survival of ecosystems. But the quality of the soil is endangered by human activities such as industrial emissions or pollution erosion [8] [9] [10]. So it is not surprising that there is a stated goal of the EU soil protection strategy to prevent further soil degradation, to preserve soil functions and to achieve an increasing public awareness of the need to protect soil [11]. In Germany 2009 daily 94 hectares natural area were sealed. The goal is to limit the sealing of natural areas to 30 hectares per day by 2020 [12].

2.3 Relevance of environmental system air

Currently most attention is paid to the air pollutant emissions. According to the Federal Emission Control Act air pollution is defined as "changes in the natural composition of the air from smoke, soot, dust, gases, aerosols, vapors and odors" [13]. Another term related to the environmental system air is the

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

greenhouse effect. The greenhouse effect describes the disturbance of the balance between heating and cooling of the earth, and is caused by greenhouse gases such as carbon dioxide, methane, nitrous oxide and other substances that affect the climate [14]. With the legal validity of the Kyoto Protocol in February 2005, the international community has committed to implement binding action objectives and instruments to implement the global climate protection [15]. The target of the German government is a reduction of greenhouse gases by 40% until 2020 [16].

2.4 Need for action

Water, soil and air are the heart of our natural ecosystems and have a major impact on biodiversity and life on earth. To protect and maintain their functionality is not only of interest in politics, but also for many companies. A recent study that was conducted in 2012 among 2.000 small and medium-sized enterprises (SME) by the Fraunhofer project group process innovation at Bayreuth University underlines the importance of environmental aspects. In this study 83% of the interviewed SMEs responded that either green products, manufacturing processes or factories are in demand in the future. 30% suspect that this will happen even in the short term, so in the next 1-3 years [17]. 31% of surveyed SMEs think that the green impact on process chains and production procedures will increase.

The current practice in SMEs, however, displays a different picture. In SMEs investments in new technologies are mainly chosen on the basis of an economic and technical point of view - and hardly consider any ecological aspects. The reason is that especially for SMEs, practical assessment methods to gain the necessary transparency of process chains' impacts on the environmental systems such as water, soil and air are missing.

The following described holistic ecological assessment represents a practical approach that combines all three environmental systems water, soil and air. Through this approach manufacturing companies, especially SMEs, should be helped to evaluate the environmental effects of their processes completely, comprehensively and to adjust their production environment-friendly.

Due to the increasing environmental awareness and the demand for ecologically transparent products and processes, many different ecological assessment methods are available. Lots of the resulting methods are geared to the framework for life cycle assessment (LCA) according to DIN EN ISO 14040 including definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase as well as the life cycle interpretation phase [18]. Although lots of ecological assessment methods are based on this norm, many LCA are created in the context of a specific actor or individual interests and therefore are always very subjective [19].

The cumulative energy demand (in German: KEA) for example is defined according to VDI 4600 as the amount of the energy expenses and includes all process-specific consumptions that are not consumed in the process, but is retained in the final product. KEA wants to assist in making energy technological data available and comparable within a uniform framework. So KEA confirms only one dimension [20]. Also the methods "Carbon Footprint" (environmental system: air) or "Virtual Water" (environmental system: water) use only one dimension.

Besides, some methods like the "Critical volumes" method (environmental systems: water, air) or the "Method of the Federal Environment Agency" (different environmental systems) assess more than one environmental system. The latter one tries to develop a comparative classification or rank formation of different environmental impacts in terms of prioritization. Furthermore the life cycle inventory analysis results (LCI results) for each impact category are aggregated and then classified in a final step and placed in a rank order. So several different environmental effects must be placed in a rank order against each other and it has to be decided, which environmental category weighs heavier.

All the various LCA methods have different frameworks and are designed with different priorities and objectives. Only a few existing approaches can be adapted for a holistic ecological assessment that focus on the three environmental systems water, soil and air. Following a new integrative approach, which combines the strengths of different ecological assessment methods, is presented.

3 CONCEPT OF THE METHODOLOGY

The presented approach is intended to help companies, especially SMEs, to evaluate, analyze and improve the choice of their production processes in a holistic way. So there are connections to the environmental management systems according to ISO 14001:2004 and also to life cycle assessments according to DIN EN ISO 14040 and 14044.

3.1 Method selection

Holistic in this context means that all three environmental systems water, soil and air are considered. The presented approach is an integrative approach which connects the strength of the most suitable assessment methods in their area for all three environmental systems. Therefore, three out of twelve possible methods were selected and were evaluated by experts according to different criteria. The most important criteria are:

1. Implementation in manufacturing technologies
   Many methods have been developed for other areas, such as agriculture. These are not really suitable for transfer to manufacturing technologies.
2. Effort to data collection
   The target of this new approach is to ensure suitability for daily use. Therefore, the data collection for the application of each method should not be too elaborate.
3. Data quality
   In addition, the quality of the input data used in the method is important. Depending on the method this can vary greatly.
4. Expenditure of time
   The presented approach should not be too exceeding and too time-consuming in data collection.

The selected methods for the three environmental systems are:

- environmental system water: "Ecological Scarcity method"
- environmental system soil: "LANCA method"
- environmental system air: "Global Warming Potential"

The methods are described in more detail below.

3.2 System boundaries

According to DIN EN ISO 14044 the system boundary determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal but can vary widely [21]. The system boundaries will be illustrated with reference to the environmental impact of CO_2 on the environmental system air. Figure 1 shows the result of a cradle-to-gate analysis of a value chain of automotive components measured in kg CO_2eq.

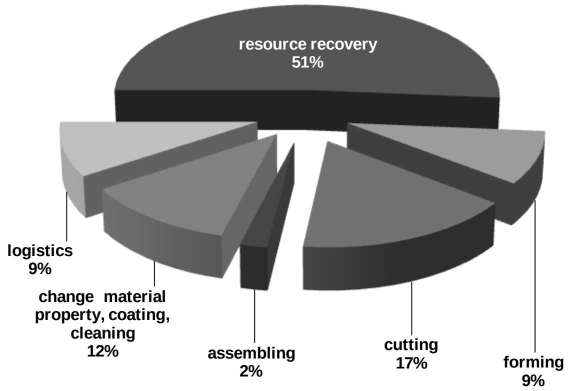


Figure 1: Analysis of value chain of automotive components ("cradle-to-gate") measured in kg CO2eq [22].

It can be shown that energy-intensive processes of resource recovery with 51.33% presents the largest percentage of CO_2eq in the new production. These processes are often parts of preliminary processes of the supply chain. Especially SMEs, due to their low purchase quantity and low market power, are not really able to influence their raw material suppliers. For SMEs, however the CO_2 effect of their manufacturing processes, like cutting or forming, are much more important. These are the CO_2 emissions SMEs can influence. According to this influences of the system boundaries the following model is composed.

3.3 Model description

The model for the presented approach considers a sequence of particular processes, in which a raw material is manufactured into a product (see Figure 2). In this case, the material which is transformed into the product is not considered, because SMEs are not able to influence the ecological impact of the raw material, as already described. Cleaning operations provide the functionality of the tool safety and are therefore seen as part of the process chain. The system boundary line is drawn at all particular processes that compose the complete process chain. Therefore, in accordance with ISO 14044, the gate-to-gate approach is applied. So this approach has a more specific framework than a general LCA.

3.4 Water assessment using "ecological scarcity"

This method is a material flow-based evaluation method and is used for the life cycle impact assessment. The input variables are the life cycle inventory analysis results. The result is expressed in "eco-points" (EP) [24]. The method uses the “distance-to-target” principle and defines the current flow in relation to defined limits, specifications or guidelines. By differentiation between a country and a reference area regional variations can be considered. In this case only the German territory and also no reference substance are considered.

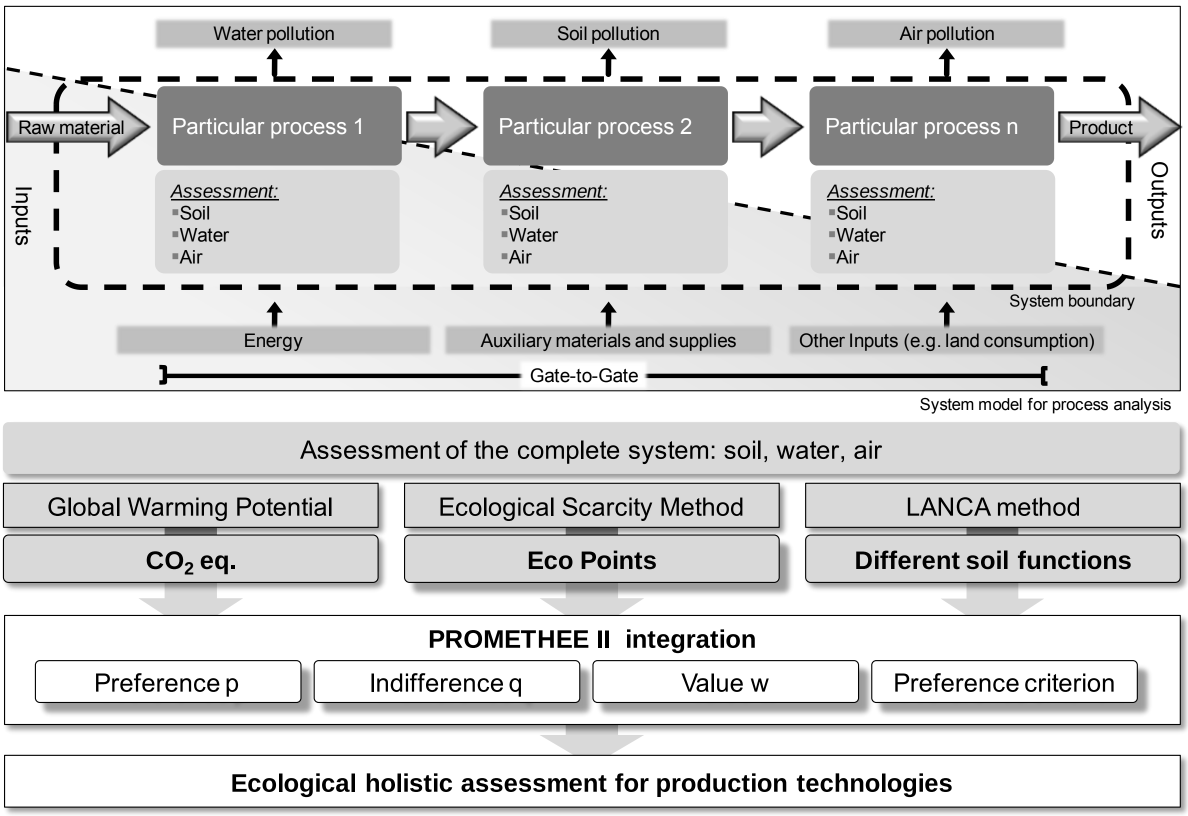


Figure 2: System model for process analysis (according to [23]) and ecological holistic assessment for production technologies.

3.5 Soil assessment using "Land Use Indicator Value Calculation in Life Cycle Assessment - LANCA"

The LANCA method quantifies the effects of different land uses on land functions for an application within LCA. According to [10] only two principal approaches survived: Land use quantification using biodiversity and land use quantification using soil functionality.

LANCA pursues the objective of a low effort for the data collection and needs fewer assumptions. In the LANCA method different soil qualities are compared at different points in time (see Figure 3). LANCA distinguishes between Occupation und Transformation, whereas Occupation [m²*a] is defined as the occupation of an area during the time of its use and Transformation [m²] is the irreversibly affected area of a land use [10].

The LANCA method rated these two parameters Occupation and Transformation in four different soil functions:

- ER - Erosion Resistance
- MFC - Mechanical Filtration Capacity
- PFC - Physiochemical filtration Capacity
- GR - Groundwater Replenishment

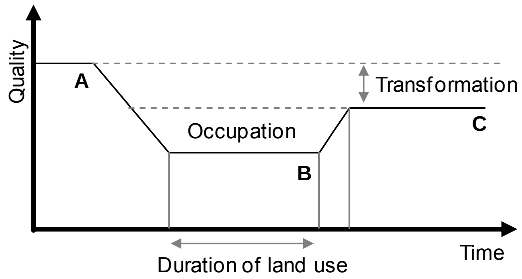


Figure 3: Land Occupation and Transformation [10].

3.6 Air assessment using "Global Warming Potential"

The assessment of emitted Greenhouse Gases (GHG) is based on the so-called Global Warming Potential (GWP) method. The GWP was developed in 1990 by the Intergovernmental Panel on Climate Change (IPCC) and later used in the Kyoto protocol [25]. The GWP is divided into a direct and indirect GWP. Especially indirect GWP have a strong dependence of time and place. As is common practice, all CO_2eq. mentioned in this paper refer to a time frame of 100 years [3].

3.7 Integration method

The result of the method of ecological scarcity, the LANCA method and the GWP method are many output values, which are independent from each other. These values are comparable for each of the individual processes, but have no relation to each other. To achieve comparability of process chains, a further characteristic value has to be developed through an integration method (see Figure 2).

This integration method is the approach of Multi-Attribute Decision Making (MADM), which assumes that the decider is not aware of the preferences between his decisions. In the MADM approach two methods, function-based and relation-based, are distinguished. Especially the relation-based method can show preferences between decision options. This opens the possibility to perform ratings, also with incomplete information. To assess the manufacturing process's influence on the different environmental systems water, soil and air the possibility of comparison and the consideration of weak preferences is necessary. The acceptance of weak preferences is an advantage over a utility analysis.

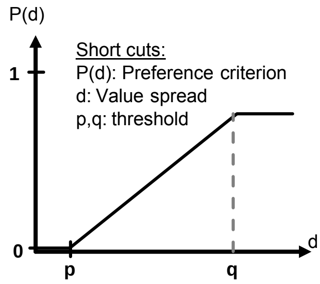


Figure 4: Criterion with linear preference with indifference area [26].

The applied Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE II) in the following is a relation-based method and has gained more and more importance in the past.

The PROMETHEE II method works with different preferences and a pairwise comparison of all dimensions (in this case the three environmental systems). The preference criterion can be chosen from six different options [27]. The appropriate step function in this case is a linear preference with indifference area (see Figure 4). Then the thresholds, the indifference q and the preference value p, need to be defined. The values and weights are subjectively determined by the decider, depending on which dimension is more important. As result the decider gets a complete ranking of options [28] [29].

4 APPLICATION ON THE BASIS OF AN EXAMPLE

The approach described above is illustrated by an example. As a simple example, a single-stage milling process is considered. A complex aluminum part with six small holes, one large hole and two slots has to be manufactured in wet processing with cutting fluid use. The system boundary line is drawn at the machine and the necessary operating, storage and transport areas, but without social, sanitary and administrative areas. In the following, an existing production technology T1 is to be compared with two alternative production technologies T2 and T3. T2 is an advanced technology that requires slightly larger area, but due to the shorter processing time less electric energy, but more cutting fluid is required. T3 is a technology similar to T1 that requires also slightly larger area than T1, but due to the longer processing time required more electric energy, but less cutting fluid. All of the following analyzes were created with data from the scientific database Ecoinvent.

First, the influence of a milling process on the environmental system water is considered, especially the pollutants Phosphorus, Chemical oxygen demand (COD), Short Chain Chlorinated Paraffin (SCCP), Phenols and others. The comparison of the three production technologies are shown in Figure 5.

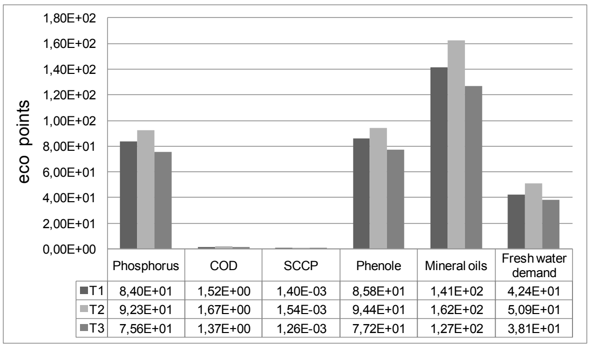


Figure 5: Results of water assessment.

To calculate the impact on the environmental system soil, different inputs are needed which can be extracted from maps, such as the EU Soil Atlas and soil analyzes. As described above, the four soil functions have to be analyzed in terms of Occupation and Transformation. Concerning the comparison of different production technologies, these data do not change, only the area occupied by the technology. Furthermore only the Occupation is considered, because this is the status to be evaluated at the end of use of the soil. It was assumed that the soil after use as a production area is still partially sealed. The results of the soil assessment are shown in Figure 6.

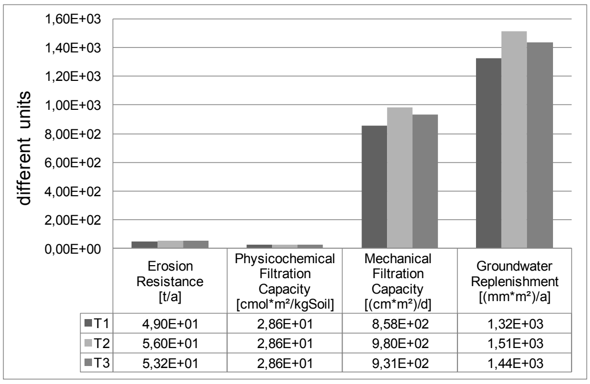


Figure 6: Results of soil assessment (Occupation).

For the impact calculation on the environmental system air especially the electrical energy is considered, furthermore the air emissions from cooling lubricant and fleece (see Figure 7).

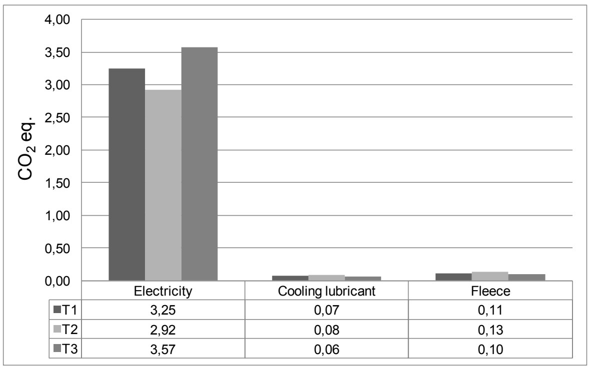


Figure 7: Results of air assessment.

Finally, the results of all the three methods LANCA, Ecological Scarcity and GWP were merged by the PROMETHEE II method. As already mentioned, it is important to define the thresholds, the indifference q and the preference value p. In this example, the threshold values result from the average values. The indifference value q is defined as 10% and the preference value p as 90% the average values of each of them. These values can be changed on each individual decider. Each criterion is also assigned by a weighting. In this case, all criteria are equally weighted. From this follows that each criteria value for water (EP) and air (CO_2eq.) is 1/3. For the four different soil functions a value each of 1/12 is used.

Table 1 shows the different rankings of the production technologies depending on the different valuation methods. In this case, the GWP method assesses technology T1 with the third rank in comparison to the other two technologies. In comparison, the Ecological Scarcity method assesses the same technology T1 with the first rank. Under the given conditions, according to the PROMETHEE II method, technology T3 should be preferred to the current technology T1. In contrast T2 is worse than the current technology T1.

Table 1: Results of the ecological holistic assessment.

Ranking	T1	T2	T3
Eco. Scarcity [EP] (water)	2	3	1
LANCA [ER] (soil)	1	3	2
LANCA [PFC] (soil)	1	1	1
LANCA [MFC] (soil)	1	3	2
LANCA [GR] (soil)	1	3	2
GWP [CO2] (air)	2	1	3
Ranking by PROMETHEE II	**2**	**3**	**1**

5 CONCLUSION UND OUTLOOK

In this paper, an ecological holistic assessment approach was presented, which not only assesses the impacts on the environmental system air but also on water and soil. Therefore, an assessment method for each environmental system was selected, which was specifically developed and optimized for the evaluation of the specific environmental system. Afterwards the results of each method were merged by the use of an integration method. The PROMETHEE II method can create a ranking, even if the decider does not know his preferences between the possible options or information are missing,

As a part of further research work additional support for the application and implementation of the PROMETHEE II method should be developed. For example, ranges for practical thresholds could be developed. Furthermore, the interdependencies between the various environmental systems should be examined in more detail. On the one hand the same influences cannot be calculated twice and on the other hand reinforcing or weakening effects between the environmental systems must be taken into account.

6 REFERENCES

[1] N.N., The ISO Survey of certifications 2011, 2012, online available: http://www.iso.org/iso/iso-survey, last review: 16.03.2013.

[2] Marcus Pratsch; Matthias Dürr, 2012, Investieren im Kontext von Klimaschutz, CDP Deutschland, Österreich, Schweiz 350 Klimawandel-Bericht 2012, DZ Bank AG, Berlin, online available: https://www.cdproject.net/CDPResults/CDP-DACH-350-Report-2012.pdf, last review: 14.04.2013.

[3] Kappas, Martin, 2009, Klimatologie, Spektrum Akademischer Verlag, Heidelberg.

[4] UNESCO, 2012, The United Nations world water development report 4, Luxembourg.

[5] Arle, J., Blondzik, K. et al., 2010, Wasserwirtschaft in Deutschland, Federal Environment Agency Germany, online available: .http://www.umweltbundesamt.de/ uba-info-medien/3470.html, last review: 14.04.2013.

[6] Koehler, A., 2008, Water use in LCA: managing the planet's freshwater resources, Int. J. Life Cycle Assessment 13.

[7] Klöpffer, W., 2009: LCA Wirkungsabschätzungsmethoden und Querverbindungen – Unterschiede zum Risk Assessment, in Ökobilanzierung 2009, Feifel, S. et al. (Hrsg.), KIT Scientific Publishing

[8] Baitz, Martin, 2002, Die Bedeutung der funktionsbasierten Charakterisierung von Flächen-Inanspruchnahmen, Shaker Verlag, Aachen.

[9] Blume, H.P; Scheffer, F.; Schachtschabel, P., 2010, Lehrbuch der Bodenkunde, Spektrum Akademischer Verlag GmbH, Heidelberg.

[10] Beck, T.; Bos, U.; Wittstock, B.; Baitz, M.; Fischer, M.; Sedlbauer, K., 2010, LANCA - Land Use Indicator Value Calculation in Life Cycle Assessment - Method Report, online available: http://www.lbp-gabi.de/files/lanca_website.pdf, last review: 16.03.2013.

[11] Kommission der Europäischen Gemeinschaften, 2006, online available: http://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/ kom_bodenschutz_vorschlag.pdf, last review: 14.04.2013.

[12] Federal Bureau of Statistics Germany, 2012, Nachhaltige Entwicklung in Deutschland Indikatorenbericht 2012, online available: https://www.destatis.de/DE/Publikationen/Thematisch/Umweltoekonomische Gesamtrechnungen/ Umweltindikatoren/IndikatorenPDF_0230001.pdf?__blob=publicationFile, last review: 14.04.2013.

[13] Bundes-Immissionsschutzgesetz, part 1, §3, online available: http://dejure.org/gesetze/BImSchG/3.html, last review: 14.04.2013.

[14] Federal Bureau of Statistics Germany, 2012, Umwelt - Erhebung bestimmter klimawirksamer Stoffe, online available: https://www.destatis.de/DE/ Publikationen/Thematisch/UmweltstatistischeErhebungen/Luftreinhaltung/

ErhebungKlimawirksamerStoffe5324201117004.pdf?__blob=publicationFile, last review: 14.04.2013.

[15] Federal Environment Agency Germany, 2012, Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2012, Dessau

[16] Federal Environment Agency Germany, 2012, press release, Röttgen: Minderung der Treibhausgasemissionen ein großer Erfolg; Dessau-Roßlau

[17] Freiberger, S., Süchting, M., Kafara, M., Müller, R., Technologie-Roadmap Oberfranken – Ergebnisse der Datenerhebung „Technologie-Roadmap Oberfranken". Fraunhofer - Projektgruppe Prozessinnovation am Lehrstuhl Umweltgerechte Produktionstechnik, Bayreuth, 2013.

[18] ISO 14040:2006: Environmental management -- Life cycle assessment -- Principles and framework, International Organization of Standardization

[19] Schmitz, s., Paulini, I., 1999, Bewertung in Ökobilanzen, online available: http://www.umweltdaten.de/publikationen/fpdf-l/3619.pdf, last review: 22.04.2013.

[20] VDI Richtlinie 4600: Kumulierter Energieaufwand (KEA)-Begriffe, Berechnungsmethoden, 2012, Verein Deutscher Ingenieure, Düsseldorf.

[21] DIN Deutsches Institut für Normung e.V., 2006, Umweltmanagement-Ökobilanz-Anforderungen und Anleitungen (ISO 14044:2006), Beuth Verlag, Berlin.

[22] Köhler, D.C.F., 2011, Regenerative Supply Chains, Shaker Verlag, Aachen.

[23] Steinhilper, R., Süchting, M. Kruse, A., Westermann, H.-H., 2012, How Complexity in the Field of Production Planning and Control influences CO2 Emissions, in Proceedings: 10th Global Conference on Sustainable Manufacturing, Instanbul.

[24] Frischknecht, R. et al., 2008, Ökobilanzen: Methode der ökologischen Knappheit - Ökofaktoren 2006, Öbu, Zürich.

[25] UNFCCC, 1997, Kyoto protocol to the United Nations framework convention on climate change, online available: http://unfccc.int/resource/ docs/convkp/kpger.pdf, last review: 21.04.2013.

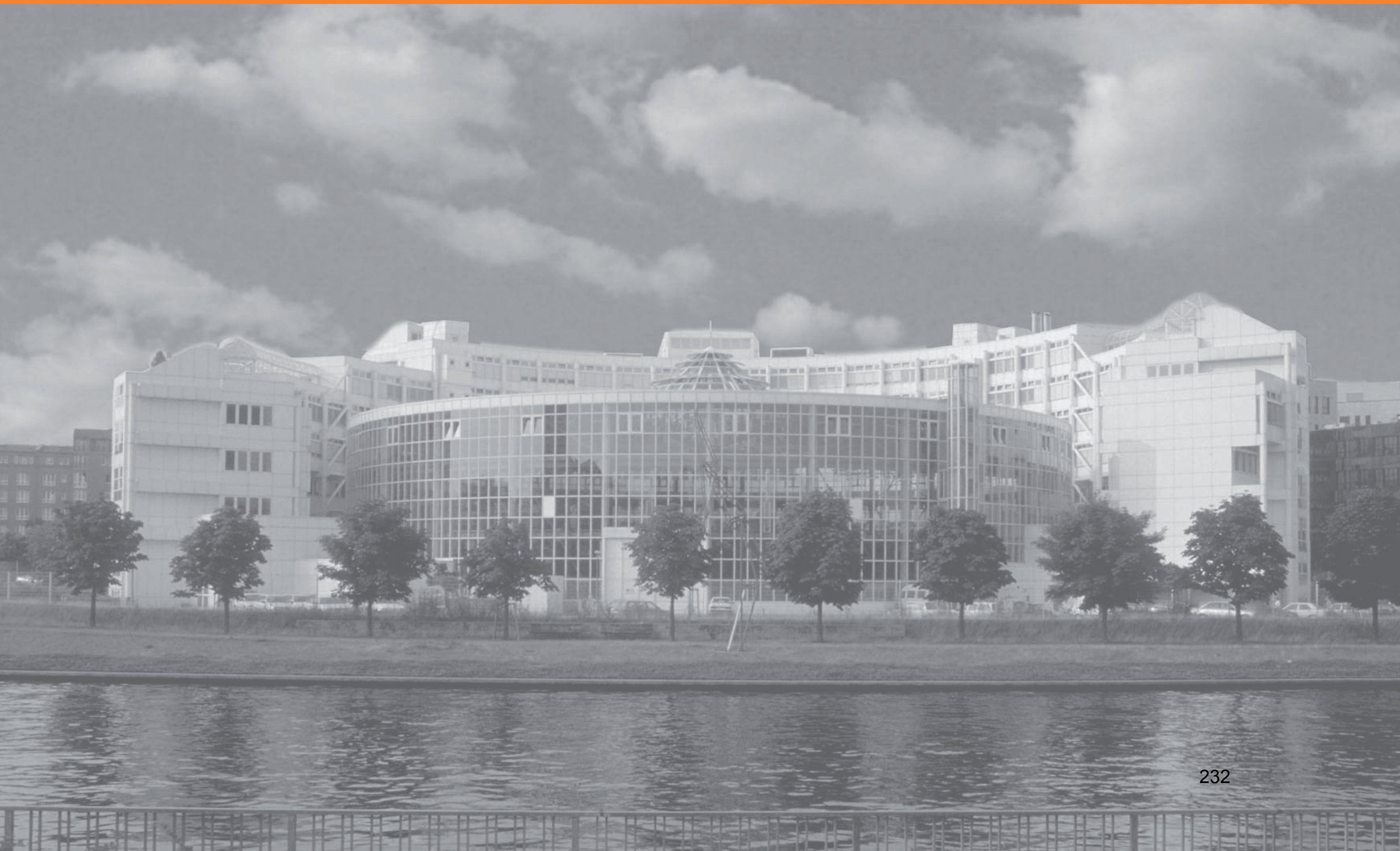
[26] Kahraman, C., 2008, Fuzzy Multi-Criteria Decision Making, Springer-Verlag, Berlin.

[27] Brans, J.P.; Vincke, P., Mareschal, B., 1986, How to select and how to rank projects: The PROMETHEE method, European Journal of Operational Research

[28] Zimmermann, H.-J.; Gutsche, L., 1991, Multi-Criteria Analyse: Einführung in die Theorie der Entscheidungen bei Mehrfachzielsetzung Springer-Verlag, Berlin, Heidelberg.

[29] Steinhilper, R., Süchting, M. Kafara, M., 2013, Total Cost and Environmental Impact of Ownership – TCEIO, ZWF, 1-2: 63-67, Carl Hanser Verlag, München.

Session 7
Maintenance



7.1 What makes cleaning a costly operation in remanufacturing?

J.R.Gamage[1], W.L.Ijomah[1], J.Windmill[2]

[1] Department of Design, Manufacture and Engineering Management, University of Strathclyde, UK

[2] Department of Electronic and Electrical Engineering, University of Strathclyde, UK

Abstract

Product remanufacturing is a widely accepted product reuse strategy in most industries due to its unique advantage of retaining a greater portion of added value in the initial manufacturing stage. Remanufacturing involves a sequence of operations including disassembly, cleaning, inspection, parts replacement, re-assembly and testing. Previous research has shown that the cost of cleaning is only second to the cost of parts replacement. The objective of this study is to illustrate the significance of the cleaning operation in automotive remanufacturing and to identify the factors influencing the cost of the cleaning process. Case studies on four UK remanufacturers, three automotive and one copier, were carried out. Seven key factors causing high cleaning costs were identified and categorised under two dimensions. These are the technical nature of the products and processes of cleaning and the business nature of the remanufacturer.

Keywords:

Automotive Industry; Cleaning; Remanufacturing

1 INTRODUCTION

Open loop supply chains were common in the early days of the manufacturing industry and even today it is the same for some industries and products. The continued extraction of natural resources and increasing adverse effects on the environment is pushing the society towards more sustainable way of manufacturing. In the context of sustainable manufacturing more attention is being paid to closing the manufacturing loop by developing methods to reuse products. One such method is remanufacturing while others are repair, recondition, repurpose and recycle. Product remanufacturing is a widely accepted sustainable product reuse strategy [1] in most industries due to its unique advantage of retaining a greater portion of added value during the initial manufacturing stages[2][3] and has developed to a faster growing business than some traditional industries [4].

Remanufacturing is quite an old concept for high value products and the term 'remanufacturing' has been used in literature with various meanings sometimes creating an ambiguity. In 1983 Lund[5] in his book on the experiences of United States' remanufacturing industry comprehensively defines remanufacturing "as an industrial process in which worn-out products are restored to like-new condition through a series of industrial processes in a factory environment, a discarded product is completely disassembled, useable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent and sometimes superior in performance and expected lifetime to the original new product". Since then many research has been conducted on this subject in variety of industries contributing some improvements and simplifications to the definition and concepts of remanufacturing. For the purpose of this paper the definition published by the British Standards Institute is used. BS 8887-220:2010 - Design for manufacture, assembly, disassembly and end-of-life processing (MADE) and BS 8887-2 Design for manufacture, assembly, disassembly and end-of-life processing (MADE) Part 2: Terms and definitions, defines remanufacturing as 'returning a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product'[6][7].

The remanufacturing process consists of several important steps (Please refer to Figure 1). Firstly the used product, which is known as the 'Core', is received at the remanufacturing facility. Then the product is fully disassembled in to part level and then each part is cleaned. For example in automotive gearbox remanufacturing, the parts would be gear box housing, all internal gears, shafts, bearings, connecting bolts and nuts, couplings and shifter mechanisms. The main purpose of cleaning is to facilitate inspection and damage correction, and thus make the parts to like new in condition. The process of cleaning requires one or multiple processes including both manual and machine operations. The correct extent of cleaning is cleaning the product up to like- new condition. However, it is difficult to measure the level of cleaning irrespectively as there is no standard yardstick available. In practice it is mostly done by visual inspection and then determining which is good enough by experience of the workers. This also causes a difference in cleaning efforts and hence costs for each remanufacturer.

The cleaned parts are then inspected for their quality and performance. Parts which fail the expected standard are either scrapped or sent for component remanufacture. Scrapped parts are replaced with new or remanufactured parts. Some critical parts which have limited operational life such as bearings are replaced with new parts irrespective of their condition to ensure the required quality and hence the required guarantee. Rebuilding of the product is then carried out by assembling the parts together according the original

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

equipment manufacturers (OEM) specification. As the last step of remanufacturing the assembled product is subjected to an operational performance test which is similar to that used to test a new product during initial manufacture. In the event of using remanufactured components, the component should also be tested individually according to OEM standards before assembly to ensure successful component remanufacture.

Almost all the remanufacturing steps discussed above are highly labour intensive and time consuming unlike the operations in initial manufacturing which may use automation. This can make remanufacturing a costly operation so that sometimes it is not worth opting for remanufacture instead of the other end-of-life processes. Compared to the other steps of remanufacturing cleaning accounts for a considerable portion of the cost of automotive remanufacturing [8]. It is of paramount importance that the costs of product recovery activities are limited to make them economically viable and hence sustainable. Therefore this research aims at investigating factors for higher costs in the cleaning process of automotive remanufacturing and suggests ways in which these costs could be reduced.

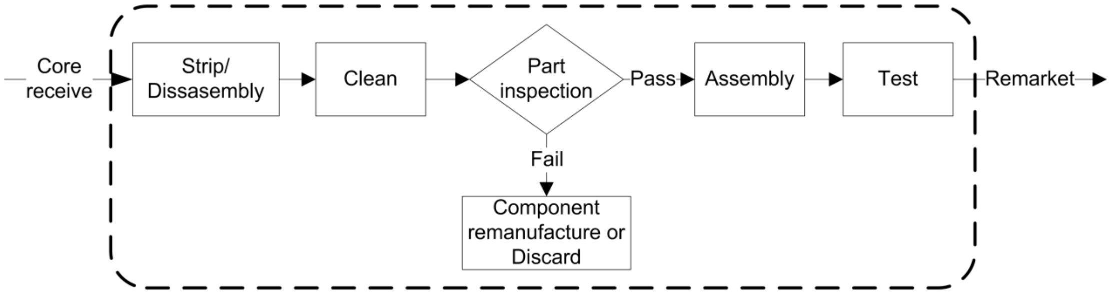


Figure 1: General process of Remanufacturing

2 LITERATURE REVIEW

Literature is enriched with a range of research on various aspects of remanufacturing in a variety of industries. It is stated that remanufactured products consumes about 50% to 80%less energy to produce when compared with a new product manufacture but with the comparable quality level [9]. Further there could be production cost savings from 20% to 80% compared with conventional manufacturing making remanufacturing a financially sound operation [2][9]. A study on environmental savings through remanufacturing of compressors has shown that the amount of greenhouse gas emission of remanufactured product is around 90% less than the manufacturing new compressor and it is 50% cheaper [10].

When it comes to automobile industry, it is estimated that 8-9 million vehicles are discarded every year in the European Union of which a major proportion is recycled meaning that an average value of 75% by weight of a vehicle is being recycled [11]. The above volume is comprised of the components that are discarded during remanufacture and components that are not considered for remanufacture. The large quantities discarded and high residual values of automobiles encourage reuse strategies to be followed. Hence it is important to develop cost effective strategies in remanufacturing. It has been found that the cost of cleaning seconds only to new parts replacement within reassembly operation in a survey undertaken in US automotive remanufacturing sector [8].

A study on the Swedish remanufacturing industry focusing on automotive and household appliances [12] has indicated that cleaning and damage correction steps are the most critical steps in the remanufacturing process. The cost for cleaning is largely from labour cost component among other capital and overhead costs. This is because there are few automated or machine assisted processes for cleaning. Other costs arise from consumables like chemical detergents and other factory overheads like electricity to operate cleaning machinery. So the time spent on cleaning is vital in controlling the cleaning costs involved. An assessment on US remanufacturing practices [13] indicates that cleaning accounts for the major portion of total remanufacturing processing time with an average of 20% spent on cleaning operation. One more reason for these excessive cleaning time is the requirement of multiple processing within the cleaning operation [4]. A study on energy intensities in diesel engine component manufacture in US[14] states cleaning remains a dominant energy consumer for remanufacturing of all of the engine components.

3 METHODOLOGY

A comprehensive literature survey on product remanufacturing was undertaken to figure out the issues of remanufacturing. The nature of the research objectives demands multiple case study approach as discussed in [15]. Four remanufacturing companies in the United Kingdom were chosen out of which three were in the automotive remanufacturing industry and the other in office equipment, (the photo copier) remanufacturing industry. Senior technical managers and operational level staff were interviewed onsite. Direct observations and company documents were used to understand the remanufacturing process in general and the importance and procedures of cleaning in particular.

4 CASE STUDIES

The entire process of remanufacturing from gate-to-gate was studied during case study visits. A comparison of case companies with regard to industry sector, category of remanufacturing, volume of operation and nature of cleaning operation is presented in Table *1*. Automotive transmission and engine components (such as gear wheels, shafts, couplings, valve bodies, torque converters, pistons, cylinder blocks, etc) require different degrees of cleaning and often done by different machine aids. Machine aided cleaning used in the case companies were, spray cleaning, baking, chemical bath agitating, shot blasting, and vibration grits cleaning. Manual washing, which is the most common, may still be required even after one stage machine aided cleaning.

Table 1 : Comparison of case companies

	COMPANY A	COMPANY B	COMPANY C	COMPANY D
Sector	*Automotive*	*Automotive*	*Automotive*	*Copier*
Nature of business	*Both automatic and manual transmission remanufacturing*	*Manual transmission and engine remanufacturing*	*diesel engines and transmissions, cylinder heads*	*Photo copier remanufacturing and after sales services*
Category	*Independent remanufacturer*	*Contract remanufacture*	*OEM*	*Independent catering for limited brands*
Company size (employees)	*25 approx.* *SME*	*75 approx.* *SME*	*300 approx.*	*15 approx.* *SME*
Average production (approx.)	*600 units/year*	*15,000 units/year*	*Complex*	*400 units/year*
Nature of cleaning operation	*Machine and manual* *Uses aqueous based detergents and degreasers*	*Varity of machines and manual* *Uses aqueous based detergents and degreasers*	*Varity of machines (Ex. vibration) and manual cleaning*	*Only Manual cleaning* *Uses aqueous based detergents*

Company A, uses a spray cleaner machine and manual cleaning of automobile transmissions parts. After cleaning they spray paints the gearbox cases in bringing those to like new condition. Whereas company B uses only cleaning techniques in bringing the gearbox casings to like-new condition. These include the spray machine wash and then shot blasting to get the natural aluminium outlook without painting it. For other inside components they use dipped cleaning with kerosene and aqueous detergents, vibration grits cleaning and manual cleaning. Company B spends 40% of its total remanufacturing time for cleaning operation during manual transmission cleaning. This has been largely contributed by the manual cleaning operation. Company C also uses manual cleaning and variety of machine cleaning techniques. It was mentioned that consumables of cleaning alone accounts for 10% from the total cost of remanufacturing in company C.

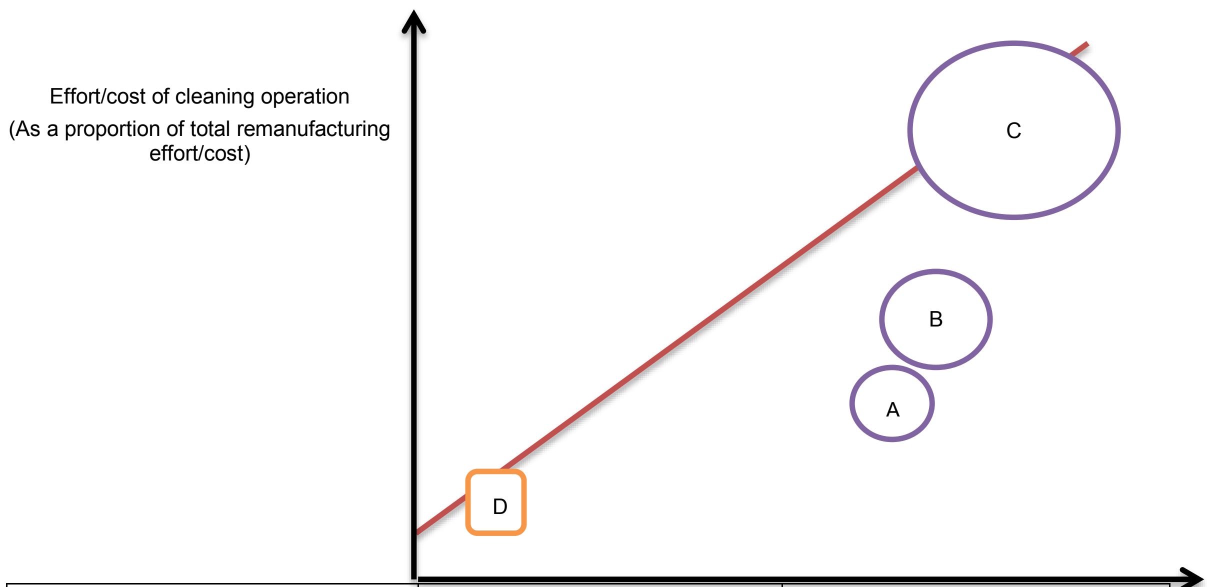
A study on automotive parts remanufacturing [8] reveals five main reasons for cleaning difficulties; namely the size of parts/orifices, environmental regulations, excess debris, material type and corrosion. These were enquired and confirmed by the case studies A, B and C. Additionally two new important factors were also found. These are the output form of the remanufactured product and the approaches to cleaning by individual remanufacturer. The attention to cleaning is higher in component remanufacture than whole unit remanufacture. For example during whole engine remanufacture versus piston remanufacture, there is much higher effort is needed for the later. This is because the customer is comparing the remanufactured component (piston) with its new counterpart. However during whole engine remanufacturing the attention/effort needed to clean the same piston would be much lesser. Some remanufacturers use finishing operations, like painting, to bring products to like new condition thus reducing the efforts of cleaning. These kinds of alternative approaches to cleaning by some remanufacturers may reduce the costs incurred for cleaning.

Attention for cleaning was comparatively low in company A, medium in Company B and high in company C. This may be due to the fact that OEMs and contract remanufacturers are much more concern about the brand value of products. Further they have to incur higher costs when complying with environmental regulations than for small scale independent remanufacturers who outsource the waste disposal. The use of technology also increases from company A to C as company wealth, volume and complexity of operation increases. Furthermore company C has to put an extra effort for cleaning as their output form of products includes remanufactured spare parts other than whole units. In contrast, company D, which is in the copier industry has a relatively lower extent of cleaning which requires only manual cleaning with aqueous detergents as it does not contain large amounts of debris and they use a final painting operation. Further copiers have fewer parts, less intricate components and simpler joining methods compared to automotive parts.

5 FINDINGS

Seven factors were identified which make cleaning costlier (please refer left most column in Figure 2). Out of which first five was mentioned in literature and also confirmed through the case studies. New two factors, output form and approaches to cleaning, were revealed through case studies. These seven factors can be categorised to two main dimensions. The first is the technical difficulty due to physical characteristics of the product and/or process which makes cleaning process more complex. This demands extended labour and machine hours adding up to the cost of cleaning. The first four factors in the list (Figure 2) belong to this category. The second dimension is the factors arising from the nature of the business of the remanufacturer. Characteristics like company scale, volume and variety of operation, output form and internal standards coupled with the brand image are concerned under business nature. The last three factors in the list could be categorised under second dimension. The costs associated with cleaning consumables, overheads and compliance to cleaning waste disposal regulations may increase due to the factors under second dimension.

Figure 2 shows the relative costs incurred for cleaning in each of the case studies. The circles represent automotive remanufacturers and square represents the copier remanufacturer. The relative size of object shows the size of the organisation in terms of employees and volume of operation. The figure is not to scale but represents a fair enough picture based on the information gained during the case studies. The x - axis represents the factors which make cleaning costlier and the y - axis represents the cost of cleaning as a proportion of total remanufacturing cost in each company.



FACTOR		
Part complexity (shape, size)	*Low*	*High*
Excessive debris	*Low*	*High*
Material type	*Easy (ex. Ferrous)*	*Difficult (ex. Aluminum)*
Corrosion	*Low*	*High*
Environmental regulations	*Low applicability*	*High applicability*
Output form	*Whole units (ex. Complete transmission or engine)*	*Part level (ex. Crank shaft, piston)*
Approaches to cleaning (due to brand consciousness and internal standards)	*Simple*	*Complex*

Figure 2 : Cost of cleaning vs factors affecting cleaning

It could be concluded that both dimensions equally contribute to the cost of cleaning. It is important to identify what are the factors that mostly affect in a given context and address them to bring down the cost of cleaning during remanufacture. Individual companies need to set their own targets in cleaning operations and invest accordingly in gaining a cost advantage.

6 SUMMARY

The factors making higher cleaning efforts have been identified. Those factors affect every remanufacturer depending on the nature of their operation and type of the products. The findings of previous research have been confirmed and some new factors were also identified. The research emphasises the significance of the cleaning operation as a high cost contributor for remanufacturing. Higher cost of remanufactured products may hinder their competitiveness in the market place which affects sustainable manufacturing. The authors believe that this knowledge would encourage product designers to consider more about the aspect of cleaning during the product design stage (Design for Cleaning) thus assisting them to design more sustainable and environmentally friendly products.

7 ACKNOWLEDGMENTS

Authors extend their sincere gratitude to all participating companies in the UK remanufacturing sector for facilitating observation visits and thanks for the interviewees at all levels for sharing their valuable experience.

8 REFERENCES

[1] P. Zwolinski and D. Brissaud, “Remanufacturing strategies to support product design and redesign,” *Journal of Engineering Design*, vol. 19, no. 4, pp. 321–335, 2008.

[2] R. Giutini and K. Gaudette, “Remanufacturing: The next great opportunity for boosting US productivity,” *Business Horizons*, vol. 46, no. 6, pp. 41–48, Nov. 2003.

[3] E. Sundin and H. M. Lee, “In what way is remanufacturing good for the environment?,” in *Design for Innovative Value Towards a Sustainable Society*, M. Matsumoto, Y. Umeda, K. Masui, and S. Fukushige, Eds. Dordrecht: Springer Netherlands, 2012, pp. 552–557.

[4] V. D. R. Guide Jr, “Production planning and control for remanufacturing: industry practice and research needs,” *Journal of Operations Management*, vol. 18, no. 4, pp. 467–483, 2000.

[5] R. T. Lund, *Remanufacturing, United States experience and implications for developing nations*. Center for Policy Alternatives, Massachusetts Institute of Technology, 1983.

[6] B. Walsh, “A new British Standard defines remanufacturing,” *Centre for Remanufacturing and Reuse (CRR)*, 14-Nov-2008. [Online]. Available: http://www.remanufacturing.org.uk/. [Accessed: 20-Mar-2013].

[7] W. L. Ijomah, “A Model-based Definition of the Generic Remanufacturing Business Process,” PhD Thesis, University of Plymouth, Plymouth, United Kingdom, 2002.

[8] R. Hammond, T. Amezquita, and B. Bras, “Issues in the automotive parts remanufacturing industry: a discussion of results from surveys performed among remanufacturers,” *Engineering Design and Automation*, vol. 4, pp. 27–46, 1998.

[9] E. Sundin, M. Lindahl, and W. Ijomah, “Product design for product/service systems: Design experiences from Swedish industry,” *Journal of Manufacturing Technology Management*, vol. 20, no. 5, pp. 723–753, May 2009.

[10] W. Biswas and M. Rosano, “A life cycle greenhouse gas assessment of remanufactured refrigeration and air conditioning compressors,” *International Journal of Sustainable Manufacturing*, vol. 2, no. 2, pp. 222–236, 2011.

[11] S. Kumar and V. Putnam, “Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors,” *International Journal of Production Economics*, vol. 115, no. 2, pp. 305–315, Oct. 2008.

[12] E. Sundin and B. Bras, “Making functional sales environmentally and economically beneficial through product remanufacturing,” *Journal of Cleaner Production*, vol. 13, no. 9, pp. 913–925, Jul. 2005.

[13] N. Nasr, C. Hughson, E. Varel, and R. Bauer, “State-of-the-art assessment of remanufacturing technology.” Rochester Institute of Technology, 1998.

[14] J. W. Sutherland, D. P. Adler, K. R. Haapala, and V. Kumar, “A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production,” *CIRP Annals - Manufacturing Technology*, vol. 57, no. 1, pp. 5–8, 2008.

[15] R. K. Yin, *Case Study Research*. London,UK: Sage, 2003.

7.2 Manufacturing strategy using new and reconditioned rotable spare parts

N. Chari[1], C. Diallo[1], U. Venkatadri[1], D. Aït-Kadi[2]
[1]Department of Industrial Engineering, Dalhousie University, Canada,
[2] Département de génie mécanique, Université Laval, Canada

Abstract
The process of remanufacturing is attractive economically and environmentally for both manufacturers and consumers. It is important to properly use reconditioned parts in a production plan based on their availability and production costs. A mathematical model is derived to find the cost-optimal production strategy that incorporates reconditioned components in the manufacturing effort. New and reconditioned parts are used to carry out replacements upon failure under an unlimited free replacement warranty policy. Key production decisions, such as when remanufacturing should commence, how long the warranty period should be, and how many returned parts should be reconditioned are answered. The availability of reconditioned parts and their discounted costs are incorporated in the model. Interactions between these decisions and their impacts on the manufacturing system and the consumer are investigated. A case study on aircraft rotable spare parts will be presented.
Keywords:
Remanufacturing; End of Life;Reconditioning;Spare Parts; Unlimited Free Replacement Warranty

1 INTRODUCTION

The five options available at a product's end of life (EOL) are: disposal, recycling, repair for use by the same consumer, re-use by another consumer, and refurbishing/remanufacturing[1,2]. Remanufacturing is the process of restoring used products to like-new conditions by disassembly, cleaning, repairing and replacing parts, and reassembly[3]. In contrast, refurbishing entails minimal disassembly, and can be thought of as a lighter version of remanufacturing[4]. Both procedures enhance the environmental and economicallure by reducing the consumption of virgin materials and energy. Moreover, the diminishing access to raw materials is forcing manufacturers to implement design methodologies incorporating global sustainability, using materials more efficiently, and participating in EOL product recovery[5]. In the refurbishing/remanufacturing EOL option, the returned product is disassembled, and used within the bill of materials (BOM) or a production plan. Potential benefits from remanufacturing are contingent on capacity utilization[6], and thus finding the ideal composition of new and reconditioned components is paramount in determining cost-effective production plans.

Economically, remanufacturing can be profitable, but it is heavily conditional on the product type and the industry. There is uncertainty in both the number of returned products and in the quality of the returns. Production plans for both new and remanufactured products were developed using a linear programming model and deterministic demand[7]. Mathematical models to deal with inventory control problems [8] and production planning[9,10]using reconditioned products have all been considered. A company must provide EOL services by supplying spare parts throughout the service period in order to remain competitive[11,12]; forcing manufacturers to carefully determine the warranty period to offer with their products.

Warranty can be thought of as a contract where consumers will have their faulty product repaired/replaced at no cost or at reduced cost, before a specified time[13]. It indirectly conveys product quality to consumers through the terms and product reliability, which then dictate the associated costs[14-17]. Similarly, a key component in the resale of the remanufactured product is the connectedwarranty that must be offered with it. An expected warranty cost equation using second-hand components at the component level was presented [18]. A new strategy using reconditioned components for the replacements was proposed [19], however in real practice it is not always possible to have access to enough reconditioned components to honour the warranty. Since the supply of EOL or returned products is not steady, a manufacturer can be forced to use a combination or mixture of new and reconditioned components to carry-out replacements[20,21]. A mathematical model to determine the proportion of new and reconditioned components to be used, the age of the reconditioned components, the warranty length, and the profit margin in order to maximize the total profit was developed [22]. The role of EOL services in the context of the product's entire lifecycle including the demand, production, inventory, and replacement upon failure during the EOL warranty period was investigated [23].

Kim and Park provided a robust production planning control model by incorporating manufacturing and EOL warranty[23]. This includes both the manufacture of the original products, as well as that of the spare parts to satisfy the warranty. The objective function consists of two major parts: the profit function for the production of new products, and the cost function to manufacture and supply spare parts as required. In the construction of the objective statement it is assumed that the company will produce and sell the product throughout its lifecycle and provide the customer with spare parts for the full length of the warranty period after the product has been discontinued. The major caveat here was that the customer could only get the spare part from the company once during the course of the entire product lifecycle – including the warranty period. This and theinability to handle reconditioned components werecrucialshortcomings of this model. In this paper, the two-stage optimal control theory model proposed by [23]is extended to account for the collection and reuse of reconditioned parts in the manufacturing process (see Figure 1) along with anunlimited free replacement warranty (UFRW) policy offered on the products. The formulation of the system's dynamics and numerical experiments will help understand the interactions between warranty length, production rate, refurbishing rate, and product reliability.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

Part failures in the airline industry can have substantial cost implications due to the disruptions that they cause; stressing the importance to estimate their failure and have access to replacement parts. Spare parts demand is usually intermittent and can be classified as: slow moving demand, strictly intermittent demand, erratic demand, and lumpy demand [24]. Regatteri et al. focus on lumpy demand while performing a case study on Alitalia [24-26]. Rotable parts require periodic replacement, and reconditioning these components can help mitigate the problems associated with their availability.

This paper is structured as follows: In Section 2, the model is introduced, the notation is defined, and the mathematical model is developed. Section 3 is dedicated to the discussion of the results obtained using the model on a rotable spare part from a Canadian carrier.

2 THE OPTIMAL CONTROL THEORY MODEL

An optimal control theory model of an MRP-based production plan using new and reconditioned components in the context of remanufacturing has been developed to determine the optimal production lifecycle length andwarranty period (Figure 1).

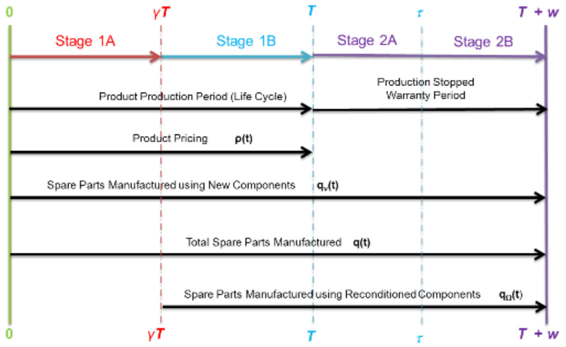


Figure 1: Model Stages

The company produces and sells a product until$T$, the end of Stage 1B, when it is discontinued. Concurrently, new spare parts are fabricated and are used to repair the products that fail during the warranty coverage period$w$. In Stage 1A, all spare parts are created using new components. The start of Stage 1B sees the introduction of reconditioned components harvested from failed products to be used in the assembly of spare parts. The next stage represents the warranty obligations of the firm after the product is discontinued. Here, there is a point (τ), where the cumulative number of product failures, $F(t)$, is for the first time equivalent to the cumulative production of new and reconditioned spare parts, $Q(t)$. All the accrued spare parts are completely consumed within Stage 2A, and subsequently spare parts are produced as required in Stage 2B. These four periods are listed below:

- Stage 1A ($0 \le t \le \gamma T$): The company manufactures the product and also manufactures new spare parts using solely new components;
- Stage 1B ($\gamma T \le t \le T$): Spare parts using both new and reconditioned components are produced;
- Stage 2A ($T \le t \le \tau$): Production of the product is discontinued, but production of reconditioned spare parts continues, and new spare parts are produced as needed;
- Stage 2B ($\tau \le t \le T + w$): Production of reconditioned spare parts continues, and new spare parts produced as needed.

With the incorporation of reconditioned components in this model, the followingadditional decisions must be considered:

1. When should the reconditioned components be introduced into the manufacturing production plan?
2. How many reconditioned parts are available?
3. What is the economic benefit?

The introduction of reconditioned components isa key factor in this investigation, where the time of commencement is defined as a fraction (γ) of the product's lifecycle (T) with $0 \le \gamma \le 1$. A value of $\gamma = 0$ means reconditioned components are utilized at time0, effectively eliminating Stage 1A; whereas $\gamma = 1$ implies that reconditioned components are introduced in the 2nd Stage. The two considerations to be made with regards to availability of reconditioned parts are: the total amount of failed products $F(t)$, and how much of it is usable η. ηrepresents the proportion of failed products that will be in a state of degradation such that their key components can technically and economically be tested, removed, and reconditioned. Lastly, there is a cost to use reconditioned components, so k_Ω will model the production cost of remanufacturing as a function ofγ. Furthermore, all pertinent terms relating to spare parts will be split into their new (ν) and reconditioned (Ω) constituents. The following notation is adopted.

w	Warranty period
T	Lifecycle of the current product
τ	Time at which cumulative production of spare parts equals the cumulative number of failure
γT	Time at which remanufacturing begins as a fraction of T , $0 \le \gamma \le 1$
$\rho(t)$	Sale price of the current product at t
$d(t)$	Instantaneous sales units of the current product at t
$D(t)$	Cumulative sales units of the current product at t
$F(t)$	Cumulative parts failuresat$t$
$q(t)$	Spare parts produced at t
$q_\nu(t)$	New spare parts produced at t
$q_\Omega(t)$	Reconditioned spare parts produced at t
$Q(t)$	Cumulative production of spare parts at t
$Q_\nu(t)$	Cumulative production of spare parts at t using new components
$Q_\Omega(t)$	Cumulative production of spare parts at t using reconditioned components
α	Failure rate
η	Proportion of failed products that can be reconditioned
h	Unit inventory cost of the spare part
d_1	Potential market size when price and warranty is zero
d_2	Price coefficient
d_3	Warranty coefficient
c_p	Unit production cost of new products
c_r	Unit cost to replace spare parts
k_i	Cost to manufacture a spare part at i, i=1,2
k_Ω	Remanufacturing parameter

The objective function is composed of 3 main parts: the profit function (sales revenue minus holding, production, and repair costs) at the first stage, the cost function at the second stage (holding, production, and repair costs) and a constant term of $mD(T) - nD(T)^2$ representing a lump sum profit (LSP) based on the market share (installed base – cumulative) held by the company. The demand increases with a longer warranty period and a lower price, however as they increase the net profit decreases. Additionally, due to economies of scale, it is cheaper to manufacture a spare part in Stage 1, but this is countered by inventory holding costs (*h*). All these trade-offs are included in Eq. ((1)):

$$Z = \int_0^T \begin{bmatrix} d(t)(\rho(t)-c_p) - h\left[Q_V(t)+Q_\Omega(t)-F(t)\right] \\ -\frac{k_1 q_V(t)^2}{2} - \frac{k_1 k_\Omega q_\Omega(t)^2}{2} - c_r f(t) \end{bmatrix} dt + \int_T^{T+w} \begin{bmatrix} -h\left[Q_V(t)+Q_\Omega(t)-F(t)\right] \\ -\frac{k_2 q_V(t)^2}{2} - \frac{k_2 k_\Omega q_\Omega(t)^2}{2} - c_r f(t) \end{bmatrix} dt + mD(T) - nD(T)^2 \tag{1}$$

Subject to:

$$Q(t) \ge F(t) \tag{2}$$

$$Q(0)=0, D(0)=0, F(0)=0 \tag{3}$$

$$t, w, T, \tau, \rho(t), d(t), D(t), F(t), q(t), Q(t) \ge 0 \tag{4}$$

First, k_Ω, the remanufacturing parameter is defined as:

$$k_\Omega = \delta_1(1-\gamma)+\delta_2 \tag{5}$$

where δ_1 and $\delta_2$are parameters to represent the slope and intercept respectively. The instantaneous demand is then:

$$d(t) = \begin{cases} d_1 - d_2\rho(t) + d_3 w, & if\ t \le T \\ 0, & if\ t > T \end{cases} \tag{6}$$

Using a two-stage optimal control model similar to[23], the Hamiltonian, the necessary conditions for optimality and the optimal solution functions are derived for each stage. Due to the limited number of pages allowed for this article, only the optimal functions are presented. All mathematical derivations are available from the authors.The first term introduced is the sale price of the product, which is modelled as:

$$\rho(t) = \begin{cases} \frac{1}{2}\left(\frac{d_1+d_3 w}{d_2} + c_p + hT\alpha t - \frac{h\alpha}{2}t^2 - X_3 \right), & if\ t \le T \end{cases} \tag{7}$$

The cumulative sales units of the product are:

$$D(t) = \begin{cases} \frac{(d_1+d_3 w)t}{2d_2} + \frac{c_p t}{2} - \frac{X_3 t}{2} + \frac{hT\alpha t^2}{4} - \frac{h\alpha t^3}{12}, & if\ 0 \le t \le T \\ \frac{(d_1+d_3 w)T}{2d_2} + \frac{c_p T}{2} - \frac{X_3 T}{2} + \frac{h\alpha T^3}{6}, & if\ T \le t \le T+w \end{cases} \tag{8}$$

With the UFRW policy as long as a product fails during the original warranty period (w), it is replaced with another product free of charge. The instantaneous failure rate is a proportion of the total volume of products under warranty coverage:

$$f(t) = \alpha\left[D(t) - V(t)\right] \tag{9}$$

and$V(t)$ is the volume of products no longer covered:

$$V(t) = \begin{cases} 0, & if\ t < w \\ D(t-w), & if\ t \ge w \end{cases} \tag{10}$$

Therefore:

$$f(t) = \begin{cases} \alpha D(t), & if\ 0 \le t < w \\ \alpha\left[D(t) - D(t-w)\right], & if\ w \le t < T \\ \alpha\left[D(T) - D(t-w)\right], & if\ t \ge T \end{cases} \tag{11}$$

Finally, $F(t) = \int_0^t f(x)dx$.

The cumulative production units of the spare parts are:

$$Q(t) = \begin{cases} \frac{ht^2}{2k_1} + \frac{X_1 t}{k_1}, & if\ 0 \le t \le T \\ \frac{ht^2}{2k_2} + \frac{X_1 t}{k_2} + \left(\frac{1}{k_1} - \frac{1}{k_2}\right)\left(\frac{hT^2}{2} + X_1 T\right), & if\ T \le t \le \tau \\ F(t), & if\ \tau \le t \le T+w \end{cases} \tag{12}$$

Similarly the instantaneous production amount is:

$$q(t) = \dot{Q}(t) \tag{13}$$

The cumulative production units and amount of reconditioned spare parts are:

$$Q_\Omega(t) = \begin{cases} 0, & if\ 0 \le t \le \gamma T \\ \eta F(t), & if\ \gamma T \le t \le T+w \end{cases} \tag{14}$$

$$q_\Omega(t) = \frac{\partial Q_\Omega}{\partial t} \tag{15}$$

Finally, the production amount and cumulative production units of new spare parts are:

$$q_V(t) = q(t) - q_\Omega(t) \tag{16}$$

$$Q_V(t) = \int_0^\infty q_V(t)dt \tag{17}$$

The integration constants resulting from the differential equations in the mathematical model are:

$$X_1 = k_2 f(\tau) - h\tau \tag{18}$$

$$X_3 = \frac{d_1+d_3 w}{d_2} + c_p + \frac{h\alpha T^2}{3} - \frac{m}{nT} \tag{19}$$

Theorem 1 *Given T, the optimal price is always increasing.*
*Proof.*The derivative of Eq. (7), arrives at:

$$\dot{\rho}(t) = \frac{d}{dT}\left(\frac{d_1 + d_3 w}{2d_2} + \frac{c_p + hT\alpha t - X_3}{2} - \frac{h\alpha}{4}t^2\right) \tag{20}$$
$$\dot{\rho}(t) = \frac{h\alpha}{2}(T-t)$$

Since$h$, α, and T are all positive quantities of holding costs, failure rate, and product lifecycle, it can been seen that the price continues to increase until $t=T$ at which point$\rho(T)=0$. When products are sold late in the lifecycle, the probability that they will fail after T increases. The reserve fund has to increase to compensate for the higher production costs of spare parts in Stage 2; increasing the price of the product.

3 RESULTS FROM A CASE STUDY

The model developed above, is applied to a case study from a large Canadian regional airline. The chosen rotable spare part is the EHSI/EADI Display (Electronic Horizontal Situation Indicator / Electronic Attitude Directional Indicator). The data obtained from the company has been partiallyanonymized, however proportions arepreserved.This model examines four key factors in the remanufacturing process: the length of the product's lifecycle (T), the warranty period (w), when to commence remanufacturing (γ), and what proportion should be reconditioned components (η).Using the parametric values shown in Table 1 arrives at an optimal solution, but also some interesting intermediary results.

Table 1: Parameters Used in Numerical Computations

Parameter	α	h	c_p	c_r	k_1	k_2	d_1	d_2	d_3	m	n
Value	0.05	1	10	5	4	8	10	1	0.2	100	0.5

The total profit in the objective function is maximized by having w as small as possible, however it is constrained by Eq.(2), which enforces that there is a greater cumulative production of spare parts at any given time to replace the cumulative failed ones. This in turn stipulates that there is a smallest allowable value of w for an associated value of$T$. These optimal pairs are shown in Figure 2. It can be seen that the value of w rises much more rapidly as the lifecycle duration increases with a noticeable change in the slope of the curve at $T\approx16$. The final feasible solution occurs at $T\approx20.7$, here$w \approx T$.

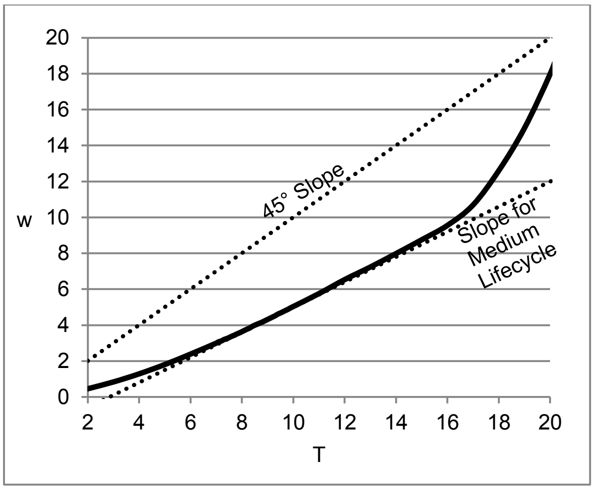


Figure 2: Optimal Warranty-Lifecycle Pairs

As T and w areincreased the probability of failure occurring during the warranty period is also increased, augmenting the cost to repair and replace. Since the bulk of the failures occur towards the end of the warranty period, an escalation of costs is seen in the 2nd Stage (Figure 3), where at $T\approx16$ the described behaviour occurs.

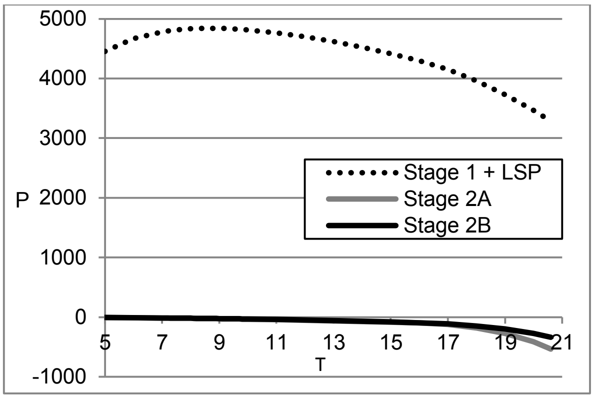


Figure 3: Profitability per Stage

Figure 4 presents the correlation between δ_1,$\delta_2$and the optimal values of η and γ. By fixing $\delta_2=0$, increasing δ_1 results in a decrease of η, and an increase in γ. The value ofη can be approximated as$(\delta_1+1)^{-1}$.

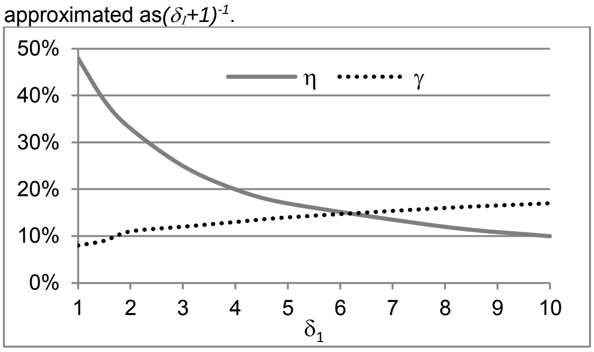


Figure 4: Relative variations of the optimal values of η and γ

For each given set of remanufacturing cost parameters,there is a clear optimal value of the four variables (Figure 5):

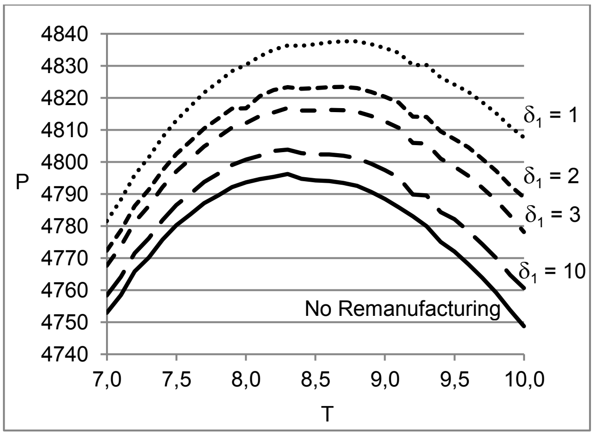


Figure 5: Profit over T ($\delta_2=0$)

Table 2 summarizes the results and trends discussed this far.

The optimal values for the no remanufacturing (baseline) scenario are: T^*=8.3, w^*=3.83, τ^*=9.55, P^*=4796.25.

Table 2: Results Summary (δ_2=0)

δ_1	T^*	w^*	τ^*	η^*	γ^*	P^*
Baseline	8.3	3.83	9.55	–	–	4796.25
1.0	8.7	4.11	10.02	48%	8%	4837.67
1.5	8.7	4.11	10.02	39%	9%	4829.15
2.0	8.7	4.11	10.02	33%	11%	4823.43
3.0	8.6	4.05	9.91	25%	12%	4816.30
4.0	8.3	3.83	9.55	20%	13%	4812.83
5.0	8.3	3.83	9.55	17%	14%	4810.14
8.0	8.3	3.83	9.55	12%	16%	4805.60
10.0	8.3	3.83	9.55	10%	17%	4803.92

The value of δ_1 not only has an effect on η and γ as previously stated, but it also dictates the optimal values of T and w. T is slightly larger when δ_1 is small, but decreases to the baseline solution as δ_1 increases. Figure 6 depictsthe dynamics of the variables for the optimal solution of $\delta_1=1$, $\delta_2=0$.

Reassessing the prior outcomes, the trends observed will be discussed, and the resultsrationalized. While it is clear that the optimal values of T, w, and γ, should neither be 0 or their maximum allowable value ($T=w=20.7$, γ=1), the intermediate optimal values of $0<\eta<1$ is an interesting quandary.There are a few reasons why these limitations exist, and they revolve around the fact that the time-line starts at the point of production of the new products. As there are not any legacy products in the market, there is not any reconditioned material available at time 0. Analogously, because products typically tend not to fail so rapidly, it takes some time for them to become accessible. In contrast, the model requires production to take place in the early stages to service failed products and to take advantage of economies of scale.

Finally, the extra holding cost from the premature manufacture of excess reconditioned parts comes into play. So, it may be possible to have too much of a good thing. The appropriate selection of δ_1, δ_2 will help determine both the time to start remanufacturing γ, and the amount of reconditioned products η to use when setting the production plan. It appears that the determination of w and T are independent of this parameter

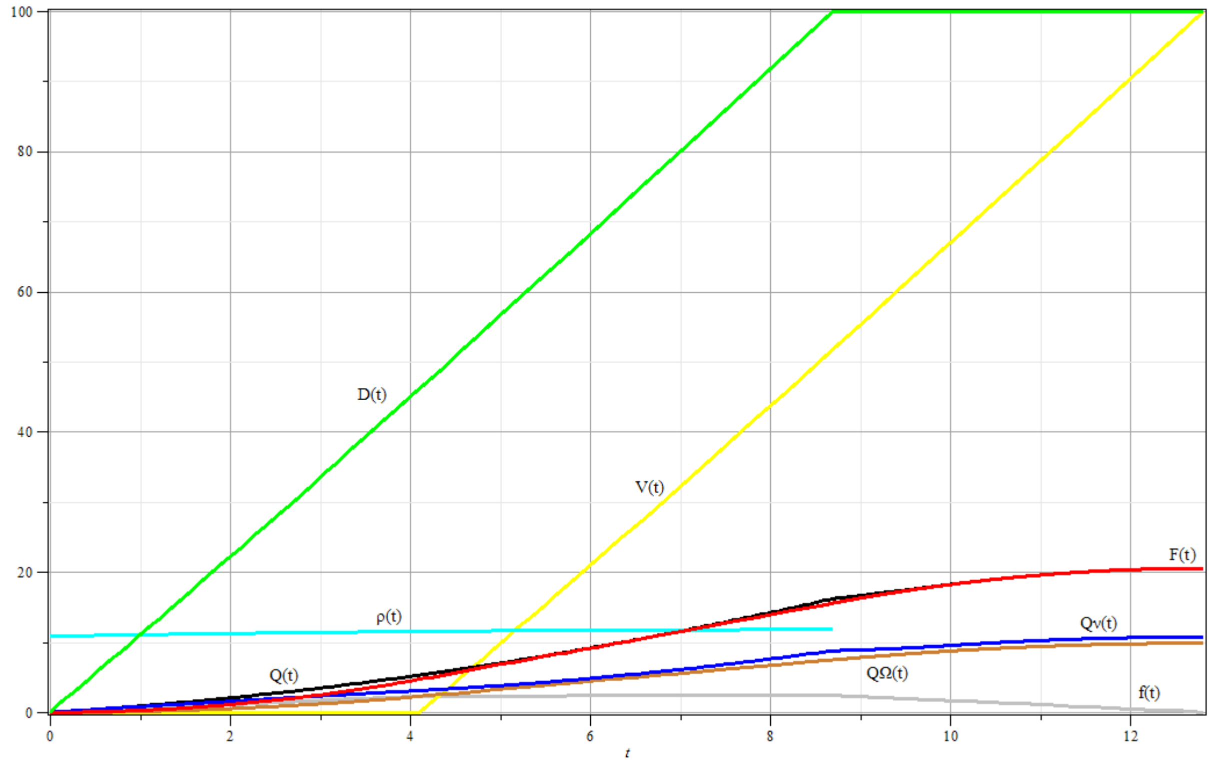


Figure 6: Dynamics in Optimal Scenario when $\delta_1=1,\delta_2=0$

4 CONCLUSIONS AND FURTHER RESEARCH

In this paper, a mathematical model for the production of spare parts with new and reconditioned components has been developed. The demand for the product was modelled to be proportional to the length of the warranty period to translate consumers' preference and perception of better reliability through longer warranty. The model obtained was solved numerically and yielded valid decision parameters that were discussed and explained. It demonstrated how an appropriate warranty model and associated production decisions can make reconditioned products attractive from both economic and environmental perspectives. The key observation in this model is that with the introduction of a declining cost parameter (k_Ω), optimal, non-zero values are established for the time to start reconditioning and the amount of reconditioned components to use. Without a declining k_Ω, the sooner reconditioning starts, the lower the overall cost, but there is an upper limit to the quantity of reconditioned components to be used in the remanufacturing effort. In all examined cases remanufacturing results in a greater profit. Extensions being investigated include using the reconditioned components in the primary production in addition to the spare parts; multiple quality grades of reconditioned components; and solving the system in a stochastic version of the problem. The current model assumed constant failure rate which is true for electronics as in the case study. For other types of components, the failure rate can be non-constant. Therefore, another extension will be to derive a model for time dependent failure rates.

5 REFERENCES

[1] B. González and B. Adenso-Díaz, "A bill of materials-based approach for end-of-life decision making in design for the environment," *International Journal of Production Research,* vol. 43, no. 10, p. 2071–2099, 2005.

[2] E. Zussman, A. Kruvet and G. Salinger, "Disassembly oriented assessment methodology to support design for recycling," *Annals of CIRP,* vol. 42, no. 1, p. 9–14, 1994.

[3] R. T. Lund and W. Hauser, The Remanufacturing Industry: Anatomy of a Giant, Boston: Boston University, 2003.

[4] M. E. Ferguson, "Strategic Issues in Closed-Loop Supply Chains with Remanufacturing," in *Closed-Loop Supply Chains: New Developments to Improve the Sustainability of Business Practices*, Boca Raton, CRC Press, 2010, pp. 9-21.

[5] S. J. Duelos, J. P. Otto and D. G. Konitzer, " Design in an era of constrained resources," *Mechanical Engineering,* vol. September, pp. 36-40, 2010.

[6] V. Verter and N. Aras, "Designing distribution systems with reverse flows," *Working Paper,* 2008.

[7] M. Denizel, M. Ferguson and G. C. Souza, "Multiperiod remanufacturing planning with uncertain quality of inputs," *IEEE Transactions on Engineering Management,* vol. 57, no. 3, p. 394–404, 2010.

[8] M. Fleischmann, J. Van Nunen and B. Grave, "Integrating closed-loop supply chains and spare parts management at IBM," *Interfaces,* vol. 33, pp. 45-56, 2003.

[9] K. Richter and M. Sombrutzk, "Remanufacturing planning for the reverse Wagner/Whitin models," *European Journal of Operational Research,* vol. 121, pp. 304-315, 2000.

[10] D. Vlachos, P. Georgiadisa and E. Iakovoua, "A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains," *Computers & Operations Research,* vol. 34, pp. 367-394, 2007.

[11] R. Teunter and L. Fortuin, "End-of-life service," *International Journal of Production Economics,* vol. 59, pp. 487-497, 1999.

[12] R. Teunter and L. Fortuin, "End-of-life service: A case study," *European Journal of Operational Research,* vol. 107, pp. 19-34, 1998.

[13] D. N. P. Murthy and I. Djamaludin, "New Product Warranty: A Literature Review," *International Journal of Production Economics,* vol. 79, no. 3, pp. 231-260, 2002.

[14] W. R. Blischke and D. N. P. Murthy, Warranty Cost Analysis, vol. 62, New York: Marcel Dekker, Inc., 1993, pp. 127-148.

[15] J. Noll, "Comparing quality signals as tools of consumer protection: are warranties always better than advertisements to promote higher product quality?," *International Review of Law and Economics,* vol. 24, no. 2, p. 227–239, 2004.

[16] J. W. Mamer, "Discounted and Per Unit Costs of Product Warranty," *Management Science,* vol. 33, no. 7, pp. 916-930, 1987.

[17] T. S. Glickman and P. D. Berger, "Optimal price and protection period decisions for a product under warranty," *Management Science, ,* vol. 22, no. 12, p. 1381–1390, 1976.

[18] G. N. Chattopadhyay and D. N. P. Murthy, "Warranty cost analysis for second-hand products," *Mathematical and Computer Modelling,* vol. 31, no. 10-12, pp. 81-88, 2000.

[19] N. Chari, C. Diallo and U. Venkatadri, "Optimal Unlimited Free-Replacement Warranty Strategy using Reconditioned Products," *International Journal of Performability Engineering,* vol. 9, no. 2, pp. 191-200, 2013.

[20] C. Diallo and D. Aït-Kadi, "Optimal mixture strategy of two identical subpopulations with different ages," in *International Conference on Industrial Engineering and Systems Management*, Metz, France, 2011.

[21] C. Diallo, D. Aït-Kadi, U. Venkatadri and N. Chari, "Reliability and warranty models for reconditioned spare parts," in *53rd Annual conference of the Canadian Operational Research Society*, St. John's, Canada, 2011.

[22] N. Chari, U. Venkatadri and C. Diallo, "Optimal Unlimited Free-Replacement Warranty Policy Using a Mixture of New and Reconditioned Components," in *Proceedings of the 4th International Conference on Information Systems, Logistics and Supply Chain*, Quebec, Canada, 2012.

[23] B. Kim and S. Park, "Optimal pricing, EOL (end of life) warranty, and spare parts manufacturing strategy amid product transition," *European Journal of Operational Research,* vol. 188, no. 3, pp. 723-745, 2008.

[24] A. A. Ghobbar and C. H. Friend, "Sources of intermittent demand for aircraft spare parts within airline operations," *Journal of Air Transport Management,* vol. 8, pp. 221-231, 2002.

[25] A. Regattieri, M. Gamberi, R. Gamberini and R. Manzini, "Managing lumpy demand for aircraft spare parts," *Journal of Air Transport Management,* vol. 11, pp. 426-431, 2005.

[26] C. H. Friend and A. A. Ghobbar, "Aircraft maintenance and inventory control: using the material requirements planning system-can it reduce costs and increase efficiency?," in *SAE Airframe Finishing Maintenance and Repair Conference and Exposition*, Jacksonville, FL, 1996.

7.3 Tool life prediction for sustainable manufacturing

J. Wang, P. Wang, and R. X. Gao
Department of Mechanical Engineering, University of Connecticut, USA

Abstract
Prediction of tool wear is essential to maintaining the quality and integrity of machined parts and minimizing material waste, for sustainable manufacturing. Past research has investigated deterministic models such as the Taylor tool life model and its variations for tool wear prediction. Due to the inherent stochastic nature of tool wear and varying operating conditions, the accuracy of such deterministic methods has shown to be limited. This paper presents a stochastic approach to tool wear prediction, based on the particle filter. The technique integrates physics-based tool wear model with measured data to establish a framework, by iteratively updating the tool wear model with force and vibration data measured during the machining process, following the Bayesian updating scheme. Effectiveness of the developed method is demonstrated through tool wear experiments using a ball nose tungsten carbide cutter in a CNC milling machine.
Keywords:
Tool Wear Prediction, Particle Filter, Bayesian Updating

1 INTRODUCTION

Advances in modern sustainable manufacturing have led to better product quality, increased flexibility and productivity [1-3]. Generally, such benefits are dependent on trouble-free operations of the various machine elements [4]. In machining industry, 20% of downtime is attributed to tool failures [5]. Therefore, tool condition monitoring and life prediction plays an important role in resulting improving machine productivity, maintaining the quality and integrity of the machined part, minimizing material waste, and reducing cost for sustainable manufacturing.

Numerous efforts have been made to develop methods for tool condition monitoring and life prediction techniques during the past two decades [6, 7]. One common approach to assess the machining performance is tool wear/life analysis [8]. The relationship between tool life and cutting speed can be described by physics-based model, such as the Taylor tool life equation [9] and its variations [8], for a selected cutting speed. However, the parameters in Taylor tool life equation are usually described using deterministic values. Therefore, they cannot capture the stochastic properties of real machining process and tool-to-tool performance variation. On the other hand, its effectiveness is also limited on a particular combination of tool and workpiece.

Increasing demand for system reliability has accelerated the integration of sensors into the manufacturing system for timely acquisition of the working status of machining tools. A general approach is to measure the process parameters that are indirectly correlated to the tool performance, such as cutting force [10], tool vibration [11], and acoustic emissions [12], spindle power [13], etc., then transforms these indirect measurements into models for condition and performance monitoring [14]. Different models have been developed and evaluated for tool wear analysis. For example, a continuous hidden Markov model is investigated using the vibration measurements for tool wear monitoring [15], An adaptive fuzzy neural network and wavelet transform are applied to tool wear condition monitoring [16]. A comprehensive review on neural network for tool wear monitoring is discussed in [17]. In [18], a multi-sensor fusion model for tool condition monitoring was developed based on different pattern classifiers (e.g., support vector machine, multilayer perceptron neural network, radial basis function neural network), and analysis results showed that the performance of support vector machine outperformed other two techniques. These above models are categorized as data driven approach. Such model may be accurate for short time prediction, but introduce high variation in long-term prediction. On the other hand, data driven approach requires a substantial amount of historical data to train the model, and obtaining the required run-to-failure data is typically a costly and time consuming process.

To tackle this problem, this paper presents a tool life prediction method based on Bayesian inference to update the physics-based model with online data measurements. The parameters in physics-based model are described using probability distribution to incorporate the stochastic property of machining process into the model. A particle filter based recursive filtering scheme is investigated to estimate the model parameters and tool state based on data measurements for tool life prediction. Tool wear test data from ball nose cutters in a CNC machines are analyzed to evaluate the presented method.

The rest of the paper is constructed as follows. After introducing the theoretical background knowledge of particle filter in Section 2, details of the particle filter based tool life prediction model is discussed in Section 3. The selection of system model and measurement model based on wear growth model and feature extraction/selection is also discussed respectively. The effectiveness of the technique is experimentally demonstrated in Section 4, based on run-to-failure data acquired using a ball nose tungsten carbide cutter

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

in a CNC milling machine. Finally, conclusions are drawn in Section 5.

2 PARTICLE FILTER

Particle filter, as one of the sequential Monte Carlo techniques, has been widely studied in applications involving high nonlinearities and/or non-Gaussianity. Such cases are difficult to model based on Kalman filter or its variations [19]. Particle filter is a recursive numerical method based on the Bayesian inference, where the posterior probability density function of a state is represented by a set of random samples (named particles) with associated weights [20].

Considering a nonlinear dynamical system, it can be modeled as:

$$x_k = f_k(x_{k-1}, u_{k-1}) \quad (1)$$

where k is the time index, x_k is the base state, f_k is the nonlinear function of state x_{k-1}, and μ_{k-1} is the sequence of process noise. The objective of prediction is to recursively estimate the state x_k from measurements z_k. The measurement model can be described as:

$$z_k = h_k(x_k, v_k) \quad (2)$$

where h_k is a nonlinear function representing the relation between measurements and state. v_k is the sequence of measurement noise. Given the measurements $z_{1:k}$ are available, the belief $p(x_k|z_{1:k})$ of state x_k can be calculated based on Bayesian theory through prediction and updating. Given the probability density function $p(x_{k-1}|z_{k-1})$ and measurements $z_{1:k-1}$ at time $k-1$, the probability density function $p(x_k|z_{k-1})$ at time k can be predicted via Chapman-Kolmogorov equation [20].

$$p(x_k \mid z_{1:k-1}) = \int p(x_k \mid x_{k-1}) p(x_{k-1} \mid z_{1:k-1}) dx_{k-1} \quad (3)$$

here, $p(x_k|x_{k-1}) = p(x_k|x_{k-1}, z_{1:k-1})$ which is described in Eq. (1) for a first order Markov process. When the measurement z_k becomes available at time k, the probability density function $p(x_k|z_{1:k})$ can be updated through Bayes' rule.

$$p(x_k \mid z_{1:k}) = \frac{p(z_k \mid x_k) p(x_k \mid z_{1:k-1})}{p(z_k \mid z_{1:k-1})} \quad (4)$$

where the likelihood function $p(z_k|x_k)$ is described in measurement model, z_k can be used to tune the prior density to obtain the posterior density of current state [20]. $p(z_k|z_{k-1})$ is the normalizing constant which is calculated as:

$$p(z_k \mid z_{1:k-1}) = \int p(z_k \mid x_k) p(x_k \mid z_{1:k-1}) dx_k \quad (5)$$

The above operations describe the recursive Bayesian approach for posterior density. However, posterior density usually cannot be determined analytically since the analytical solution in intractable. To address it, particle filter present an approach to approximate the posterior density as [20]:

$$p(x_{0:k} \mid z_{1:k}) \approx \sum_{i=1}^{N_s} \omega_k^i \delta(x_{0:k} - x_{0:k}^i) \quad (6)$$

where δ(*) is the Dirac delta function, $\{x_{0:k}^i, i = 0, ..., N_s\}$ is the random samples with associated weights ω_k^i, N_s is the total number of the random samples. k is the time index, i is the index number of random samples. There are mainly two steps in particle filter method as shown in Figure 1. Sequential importance sampling, as the first step, is used to approximate the probability distribution since the target distribution is usually difficult to obtain directly. In the first step, a number of particles are drawn to represent the importance distribution function. The importance weight of each particle is calculated accordingly to correct the importance distribution function. Sequential importance sampling helps reducing the number of samples required to approximate the posterior probability distributions, thus increasing the computational efficiency of particle filter. To avoid degeneracy of importance weights over time, sequential importance resampling as the second step is usually performed. The particles are resampled from importance distribution with associated normalized importance weights. Those particles with a very small weight are eliminated, while those particles with high weights are duplicated.

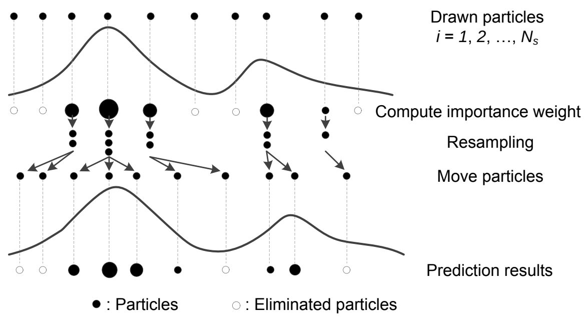


Figure 1. Visualization of sequential importance sampling and resampling.

3 TOOL LIFE PREDICTION FRAMEWORK

The tool life presents stochastic property due to many factors, such as different material property and tool-to-tool variations. On the other hand, the parameters associated with deterministic physics-based models are usually obtained from laboratory test, thus could be different from those in service due to different operating conditions. In such case, The parameters can be described in probability distribution to incorporate the stochastic property of too life prediction into the model. Particle filter can be applied to estimate both system state and model parameters. Hence, a particle filter based tool life prediction framework is formulated as shown in Figure 2. Two different types of measurements was used including direct measurements (direct indicator of tool wear severity, e.g., wear width) and indirect measurements (indirect indicator of tool wear severity, e.g., vibration, cutting force, etc.). Indirect measurements are acquired online for tool condition monitoring, while indirect measurements are obtained offline for evaluating the performance of presented method. The details of the presented method are discussed as follows.

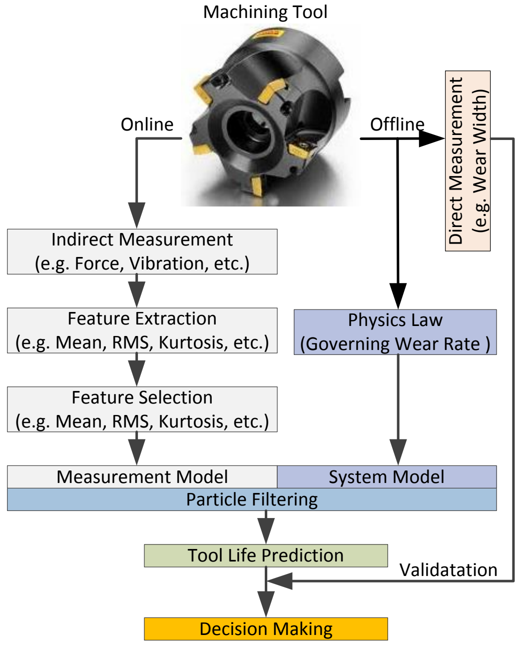


Figure 2: Framework of tool life prediction.

3.1 System model

System model is needed to describe system's state evolving behavior which could not be measured through online sensing. For Tool life prediction, wear width could be the indicator of wear severity. In [21], it showed the relationship between the wear rate and the changes of applied load. It can be expressed as:

$$d\upsilon/dt = Z/H \, N^m V_c \tag{7}$$

where *H* is the hardness of the softer in the pair of tool and work piece. *Z* represents the wear coefficient depending upon the materials and temperatures in contact. V_c is the velocity of rubbing, *m* is a constant depending on the nature of the layer removed, *N* denotes the normal load on surface [22]. Normal load can be considered as proportional to the wear width [21], which as be approximated as wear width *v*. In tool life prediction, it is usually difficult to estimate these coefficients. To circumvent the problem, an empirical model is developed by representing the defect dimension as spall area x [4]:

$$d\upsilon/dt = C\upsilon^m \tag{8}$$

Here, the model parameters *C* and *m* need to be determined. The model can be rewritten in the form of a state transition function:

$$\upsilon_k = C_{k-1}\upsilon_{k-1}^{m_{k-1}} dt + \upsilon_{k-1} \tag{9}$$

The model parameters m_{k-1}, C_{k-1} as well as damage state v_k are estimated and updated using particle filter, based on measurement model.

3.2 Measurement model

During the tool wear process, the actual wear width is generally unknown without interrupting the machining operation. On the other hand, the data analysis of vibration and cutting force has been widely employed for tool condition monitoring and remaining life prediction, since tool wear propagation can be well reflected by its vibration and cutting force. However, due to the typically low signal to noise ratio, it is difficult to model the relationship between raw data and tool wear width (denoted by measurement function h_k in Eq. 2). To tackle the problem, feature extraction is performed to reduce the data dimensionality without losing the information of tool wear signature. The relationship between extracted feature and defect size is expected to be modeled using a simple function.

Different features from the time and frequency domains could be extracted. Based on prior studies [23], statistical features are more sensitive to the tool wear. Eight different statistical features from vibration and force data are extracted including mean value, root mean square (RMS), variance, maximum value, crest factor (CF), Kurtosis, peak to average ratio (P/AR), skewness as summarized in Table 1. Different features represent different information about tool conditions. For example, RMS is a measure for the magnitude of a varying quantity. It is also related with the energy of the signal. Skewness is used to characterize the degree of signal asymmetry of the distribution around its mean, and Kurtosis indicates the spikiness of the signal.

Generally, it is difficult to determine which feature is more sensitive to tool conditions. A good feature should present consistent trend with defect propagation. In this study, Pearson Correlation coefficient is adopted to select features. Pearson correlation coefficient is a statistical measure of independence of two or more random variables which is defined as:

$$PCC = \frac{\sum_i (x_i - \bar{x})(z_i - \bar{z})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (z_i - \bar{z})^2}} \tag{10}$$

where *x* is the actual wear width, *z* is the extracted feature. The feature with highest correlation coefficient is selected as the one of interest.

Table 1: Summary of extracted features

Features	Expression
Mean value	$\bar{X} = 1/N \sum_{i=1}^{N} \lvert x_i \rvert$
RMS	$X_{RMS} = sqrt((x_1^2 + x_2^2 + \cdots + x_N^2)/N)$
Variance	$X_{var} = 1/N \sum_N (x_i - \bar{X})^2$
Maximum	$X_M = \max(x_i)$
CF	$C_F = X_M / x_{RMS}$
Kurtosis	$X_{KURT} = 1/N \sum_N ((x_i - \mu)/\sigma)^4$
P/AR	$X_{PAR} = X_M / \bar{X}$
Skewness	$X_{SKEW} = 1/N \sum_N \left(x_i - \mu / \sigma \right)^3$

4 EXPERIMENTAL STUDY

4.1 Experimental setup

To experimentally analyze the performance of the developed particle filter-based tool life prediction method, a set of tool wear test data measured from a high speed CNC machine (Roders Tech RFM760) while performing drying milling is analyzed [14]. The spindle speed was 10,400 rpm. A two-flute ball nose tungsten carbide cutter was tested to mill a workpiece of stainless steel (HRC52) in down milling operations. The feed rate was set as 1,555 mm/min. The workpiece has been pre-processed to remove the original skin layer containing hard particles. A Kistler quartz 3-component platform dynamometer was mounted between the workpiece and machining table to measure the cutting forces. In addition, three Kistler piezo accelerometers were mounted on the workpiece to measure the machine tool vibrations during the cutting process, in the x-, y-, and z- directions, respectively [14]. Figure 3 shows a diagram of the experimental setup.

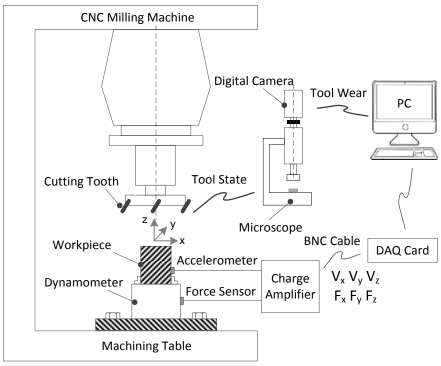


Figure 3. Schematic diagram of experimental setup.

During tool wear test, force and vibration data in three directions (x, y, z) was recorded at the sampling frequency 12 kHz using NI PCI1200 data acquisition and was then saved in a computer. The flank wear of each individual tooth was measured by a LEICA MZ12 microscope after finishing each surface (cutting depth 0.2 mm). A total of 300 data files were collected to record the tool wear process. The features discussed in Table 1 were computed and extracted from force and vibrations signals in these 300 data files to construct the measurement model. Figure 4 shows the extracted normalized features from force signal in the y-direction, and measured normalized flank wear. From these features, a saw-tooth-like behavior is identified, which can be attributed to the switching of the cutting layers during the machining experiments. Such switching operation is modeled as measurement noise in the measurement model. Next, Pearson correlation coefficient between each feature and actual wear was calculated as shown in Table 2.

The mean of force signal in the y-direction was selected to construct the measurement model, since it has the highest correlation coefficient (0.959). To study the effect of fusing multiple features to possibly improve the correlation, feature fusion based on the Principal Component Analysis (PCA) was also performed in this study, and a correlation coefficient of 0.956 with the tool wear length was obtained. Since this value is lower than 0.959, the mean force in the y-direction was selected to construct the measurement model.

Table 2: Correlations between the extracted features and actual tool wear length

	Force			Vibration		
	X	Y	Z	X	Y	Z
Mean	0.885	0.959	0.942	0.943	0.936	0.955
RMS	0.878	0.949	0.942	0.942	0.936	0.956
Variance	0.911	0.944	0.943	0.937	0.935	0.947
Maximum	0.928	0.912	0.947	0.934	0.928	0.949
CF	0.707	0.799	0.599	0.892	0.868	0.897
Kurtosis	0.182	0.703	0.514	0.655	0.527	0.582
P/AR	0.414	0.880	0.662	0.432	0.539	0.591
Skewness	0.106	0.766	0.494	0.690	0.555	0.666

The measurement model is given as:

$$z_k = x_k + v_k \tag{11}$$

where z_k represents the extracted feature, e.g. mean value of force signal in y-direction, x_k denotes the system state, characterized by tool wear width. v_k is the measurement noise.

In the system model, a tool wear growth model is needed by taking into consideration the model parameters as a probabilistic distribution. In this study, the model parameters C and m shown in Eq. 9 are modeled as uniform distributions. Based on the tool wear growth model (denoted by Eq. 9) and measurement model (denoted by Eq. 11), particle filter is performed to predict the tool wear growth. Figure 5 shows the low-term (45 steps ahead) prediction result using particle filter. It is found that the median of predicted tool wear width is close to follow the trend of actual wear width of tool. The maximum error between the median of predicted tool wear width and the actual wear width is around 5%, thus confirming the effectiveness of presented method for long-term tool life prediction.

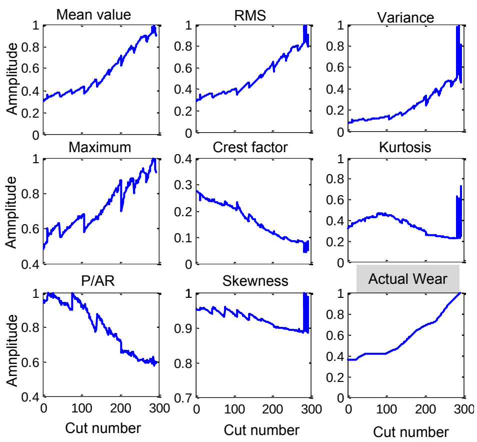


Figure 4. Extracted features from force sensor in y-direction.

5 CONCLUSIONS

Prediction of tool life is an integral part in achieving sustainable manufacturing by improving a machine system's overall reliability, thus requires comprehensive and systematic study. This paper presents a particle filter-based tool life prediction framework. A physical-based tool wear rate model is chosen as the system model, which described the governing physics of the tool wear process. The mean value from force signal is selected as the feature of interest to construct the measurement model, based on the correlation criterion. The performance of the developed method is demonstrated b using wear tests of ball nose tungsten carbide cutters in a CNC milling machine, and good result has been received. A broad range of experiments will be performed as future studies to investigate the robustness of the particle filter based method, under different operating conditions.

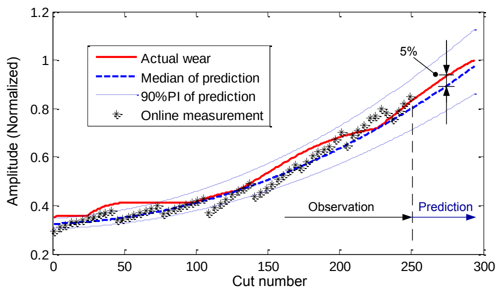


Figure 5. Predicted tool wear using particle filter.

6 ACKNOWLEDGMENTS

This research is partially supported by the National Science Foundation under award EFRI-0735974.

7 REFERENCES

[1] Wiendahl, H.P., Elmaraghy, H.A., Nyhuis, P., Zäh, M.F., Wiendahl, H.H., Duffie, N., Brieke, M., 2007, Changeable Manufacturing – Classification, Design, and Operation, CIRP Annals - Manufacturing Technology, 56/2:783-839.

[2] Bi, Z.M., Lang, S.Y.T, Shen, W., Wang, L., 2008, Reconfigurable Manufacturing Systems: the State of the Art, International Journal of Production Research, 46/4: 967-992.

[3] Mohring, H.C. Litwinski, K.M., Gummer, O., 2010, Process Monitoring with Sensory Machine Tool Components, CIRP Annals - Manufacturing Technology, 59/1: 383-386.

[4] Zhou, Z.D., Chen, Y.P., Fuh, J.Y.H., Nee, A.Y.C., 2000, Integrated Condition Monitoring and Fault Diagnosis for Modern Manufacturing Systems, CIRP Annals - Manufacturing Technology, 49/1:387-390.

[5] Kurada S., and Bradley C., 1997, A review of machine vision sensors for tool condition monitoring, Computer in Industry, 34:55-72.

[6] Rehorn A.G., Jiang J., Orban P.E., 2005, State-of-the-art methods and results in tool condition monitoring: a review, Int. J. Adv. Manuf. Technol., 26:693-670.

[7] Teti R., Jemielniak K., O'Donnell G., Dornfeld D., 2010, Advanced monitoring of machining operations, CIRP Annals - Manufacturing Technology, 59:717-739.

[8] Marksberry P.W., and Jawahir I.S., 2008, A comprehensive tool-wear/tool-life performance model in the evaluation of NDM (near dry machining) for sustainable manufacturing, International Journal of Machine Tools & Manufacture, 878-886.

[9] Mills B., Redford A., Manufacturing of Engineering Materials, Applied Science, London, 1983, p. 20.

[10] Bhattacharyya P., Senupta D., Mukhopadhaya S., 2007, Cutting force based real-time estimation of tool wear in face milling using a combination of signal process techniques, Mechanical Systems and Signal Processing, 21/6:2665-2683.

[11] Yesilyurt I. and Ozturk H., 2007, Tool condition monitoring in milling vibration analysis, International Journal of Production Research, 45/4:1013-1028.

[12] Jemielniak K., and Otman O., 1998, Catastrophic tool failure detection based on acoustic emission signal analysis, CIRP Annals - Manufacturing Technology, 47/1:31-34.

[13] Ghosh N., Ravi Y.B., Patra A., Mukhopadhyay S., Paul S., Mohanty A.R., Chattopadhyay A.B., 2007, Estimation of tool wear during CNC milling using neural network based sensor fusion, Mechanical Systems and Signal Processing, 21:466-479.

[14] Li. X., Lim B.S., Zhou J.H., Huang S., Phua S.J., Shaw K.C., Er M.J., 2009, Fuzzy neural network modeling for tool wear estimation in dry milling operation, Annual Conference of the Prognostics and Health Management Society, San Diego, CA, September 27-October 1, 2009, pp. 1-11.

[15] Vallejo Jr A.G., Flores J.A.N., Menendez R.M., Sucar L.E., Rodriguez C.A. 2005, Tool-wear monitoring based on continuous hidden Markov models, LNCS 3773, (Lazo M.,and Sanfeliu A., Eds.), Springer-Verlag Berlin Heidelberg, pp. 880-890.

[16] Li S. and Elbestawi M.A., 1996, Tool condition monitoring in machining by fuzzy neural networks, Journal of Dynamic Systems, Measurement and Control, Transactions of ASME, 118:665-672.

[17] Sick B., 2002, On-line and indirect measurement tool wear monitoring in turning with artificial networks: a review of more than a decade of research, Mechanical Systems and Signal Processing, 16/4:487-546.

[18] Cho S., Binsaeid S., Asfour S., 2010, Design of multisensory fusion-based tool condition monitoring system in end milling, Int. J. Adv. Manuf. Technol., 46:681-694.

[19] Sun J., Zuo H., Wang W., Pecht M.G., 2012, Application of a state space modeling technique to system prognostics based on a health index for condition-based maintenance, Mechanical Systems and Signal Processing, 28:585-596.

[20] Arulampalam M.S., Maskell S., Gordon N., Clapp T., 2002, A tutorial on particle filters for online nonlinear/non-Gaussian Bayesian tracking, IEEE Transactions on Signal Processing, 50/2:174-188.

[21] Archard J.F., 1953, Contact and rubbing of flat surfaces, Journal of Applied Physics, 24/8:981-988.

[22] Choudhury S.K., Srinivas P., 2004, Tool wear prediction in turning, Journal of Materials Processing Technology, 153-154:276-280.

[23] Dong J., Subrahmanyam K.V.R., Wong Y.S., Hong G.S., Mohanty A.R., 2006, Bayesian-inference–based neural networks for tool wear estimation, Int. J. Manuf. Technol., 30:797-807.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

7.4 Part agent that proposes maintenance actions for a part considering its life cycle

K. Nanjo [1], Y. Yamamori [1], K. Kato [1], H. Ookawa [1], H. Kawaharada [1], H. Hiraoka [1]
[1] Department of Precision Mechanics, Chuo University, Japan

Abstract
The transition from a consumption-oriented society to a reuse-based society is needed for the effective use of resources and environmental protection. However, it is difficult for a user to make appropriate decisions for maintenance of his/her parts because of the wide range of choices of action and the huge amount of information required. To support the user's decision and to promote the reuse of parts, we have developed a part agent system that manages information about individual parts throughout their life cycle. A part agent is a network agent that contains the information of its corresponding part and follows the movement of the part via the network throughout its life cycle. This paper describes a new mechanism of a part agent that proposes appropriate maintenance actions for the corresponding part by estimating its expected value, cost, and environmental load based on the predicted information about its life cycle.
Keywords:
Part agent; Life Cycle of Parts; Reuse; Life Cycle Simulation; Proposal of Maintenance Actions

1 INTRODUCTION

The effective reuse of mechanical parts is important for the development of a sustainable society [1]. To realize effective part reuse, it is essential to manage individual parts over their entire life cycle because each individual part has a different reuse history.

For reuse-based production, manufacturers need to capture the quantity and quality of the parts returned for reuse. However, with the exception of leased products such as photocopiers [2], most products, once sold, are not under the manufacturer’s control, which makes it difficult for manufacturers to predict the quantity and quality of returned parts. They may be reused in markets that are beyond the manufacturer’s control. The uncontrollable and unpredictable diversity of user behavior hinders the management of parts by manufacturers.

On the other hand, it is difficult for product users to manage and carry out appropriate maintenance of the large number and variety of parts in the manufactured products they own. The difficulty in managing all these parts—not to mention the inaccessibility of appropriate maintenance information—impedes management by users, in spite of the fact that more environmentally friendly actions are required from users if they are to reuse parts effectively.

On the basis of these considerations, we propose a scheme whereby a part ‘manages’ itself and supports user maintenance activities. For this purpose, we propose a management system that includes network agents and radio-frequency identification (RFID) tags [3] [4]. A network agent is assigned to an individual part of a product to which an RFID tag is attached. It is programmed to follow its real-life counterpart throughout its life cycle. We refer to this network agent as a ‘part agent’ [5].

The part agent provides users with appropriate advice on the reuse of parts and promotes the circulation of reused parts. Using this mechanism, consumers can also be advised about environmentally friendly ways of product use and predicted product failures.

Researchers have proposed methods to design the life cycle of products where designers select appropriate life cycle options for a product by evaluating various values throughout its life cycle [6]. The importance of the life cycle scenario and aspects of product-service systems have been recognized [7]. The evaluation of life cycle options can be made using life cycle simulations [8], most of which are based on the calculation of product flow among life cycle stages. An agent-based approach is employed when the life cycle simulation concerns an individual part [9].

However, the life cycle expected in the design phase may not be achieved, particularly in the case of parts or products with a long life cycle. Changes in economic circumstances, the development of new products and technologies, and other factors may undermine the life cycle options chosen in the design phase. We consider that robustness and an adaptive nature is important in life cycle design and execution. We believe that the part agent of our proposal can be used for this purpose.

In this paper, we propose a system for a part agent to generate advice in order to support the reuse of parts based on life cycle information. To select a life cycle path appropriate for the situation, the part agent compares possible paths by estimating their values and considering predicted behavior within the near future. This system will be applied to various estimations of the life cycle for which the part agent generates advice for the user.

The concept of the part agent system is described in Section 2. In Section 3, the proposed framework for the part agent to generate advice based on life cycle information is described. Implementation of the part agent is described in Section 4. Details and results of the life cycle simulation using the part agent are described in Section 5. Discussions and remaining

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

issues are presented in Section 6, and the paper is summarized in Section 7.

2 CONCEPTUAL SCHEME OF THE PART AGENT

The proposed part agent system is based on the following usage scenario. The system uses the part agent to manage all information about an individual part throughout its life cycle. The proposal assumes the spread of networks and high-precision RFID technology.

The part agent is generated at the manufacturing phase of the main parts, when an RFID tag is attached to its corresponding part. The part agent identifies the ID of the RFID tag throughout the part's life cycle, tracking the part's progression through the network. We chose an RFID tag for identification because RFIDs have a higher resistance to environmental stress than printed codes such as bar codes, which may deteriorate or be covered by dirt over the long period of a part's life cycle. Moreover, you can read, write and store an amount of data in RFID. These functions are not feasible by other print-based identification methods.

For a related research, Product Embedded Identifier (PEID) [10] has been developed which involves a small computing chip, an RFID tag, and sensors to support the middle and end of life of the products. In contrast to PEID system, our system aims to promote multiple reuses of individual parts that may go beyond the manufacturer's management. This requires a 'lightweight' system that can be used repeatedly without maintenance of sophisticated hardware.

Figure 1 shows the conceptual scheme of the part agent. The part agent collects the information needed to manage its corresponding part by communicating with various functions within the network. These functions may involve a product database that provides product design information, an application that predicts the deterioration of parts, one that provides logistic information, or one that provides market information. Furthermore, the part agent communicates with local functions on-site, such as sensory functions that detect the state of the part, storage functions for individual part data, and management and control functions of the product. Communication is established using information agents that are subordinate network agents generated by the part agents.

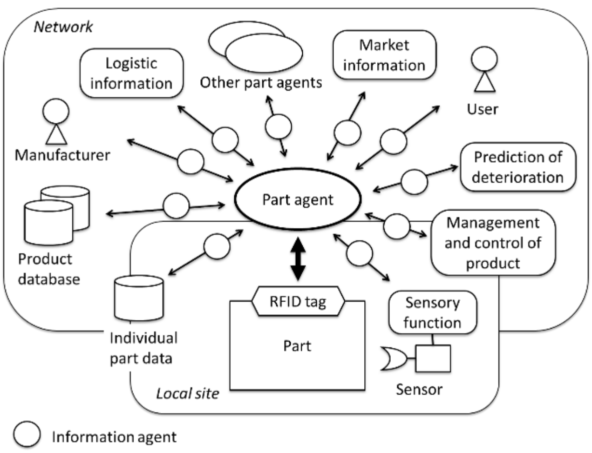


Figure 1: Conceptual scheme of the part agent.

On the basis of the collected information, the part agent provides users with appropriate advice on managing the corresponding part. Based on the advice from the part agent, the user makes a decision concerning product usage. Then, the part agent provides the necessary directions with regard to product management and control functions in accordance with the user's decision. The agent also contacts the part manufacturer regarding the repair of the part when it predicts part failure.

3 AGENT ADVICE BASED ON LIFE CYCLE INFORMATION

3.1 Framework for the part agent

It is difficult to determine the life cycle of a product in detail because one cannot predict what will happen in the future. To overcome this problem, we believe that the life cycle should be designed to allow for possible changes. As the design of robust life cycles is not a topic addressed in this paper, we simply assume that a life cycle stage in the model has multiple life cycle paths connecting to its next stages in order for the part agent to be able to select an appropriate path at the time of execution. For example, 'use' stage may have four optional paths: one leads to 'repair' stage, one to 'refurbish' stage, one to 'dispose' stage and one back to 'use' stage.

We propose, as shown in Figure 2, a basic framework for the part agent to appropriately advise the user based on the life cycle model and other related information. At each time step, the part agent performs the following procedure. First, the part agent identifies all the candidate paths from the current life cycle stage and then checks each path to see if it is 'active' or not. For example, if the part fails, then the path back to the 'use' stage (meaning that the part will continue to be used) cannot be followed and should be marked as 'inactive.'

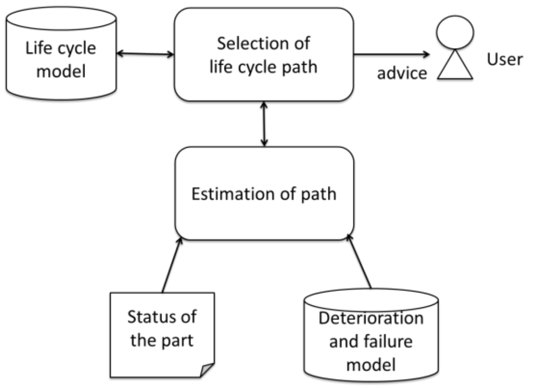


Figure 2: Framework for part agent advice generation.

3.2 Life cycle model

The part agent has information on the life cycle of the part consisting of a network of life cycle stages connected by life cycle paths. The information of the life cycle is created during the design phase of the part and is provided to the corresponding part agent. The life cycle differs depending on the type of the part.

Based on the information given in this life cycle, the part agent estimates each option of the life cycle by performing a simulation and then selects an appropriate route for the part.

3.3 Expanded life cycle model

Figure 3 illustrates our expanded life cycle model derived from the life cycle model of the part. The expanded life cycle path represents a transfer in one time step from an expanded life cycle stage to another stage. The expanded stage has values required or generated there for the step, such as cost, environmental load, and value. Multiple expanded paths may exist starting from an expanded stage as described above.

The part agent decides at every time step which path should be followed. For that purpose, the part agent estimates future possible actions. The probability assigned to each expanded life cycle path represents an estimated probability that the part agent takes that path.

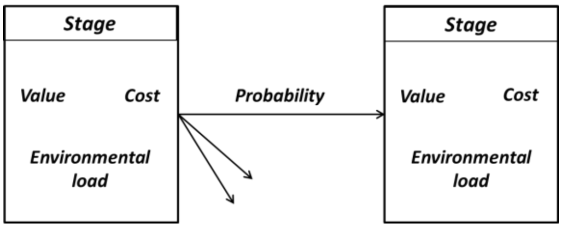


Figure 3: Expanded life cycle model.

The part agent evaluates each active expanded path. The evaluation is based on an estimation of the expanded path using information that includes the current status of the part and information about its deterioration and failure. The evaluation is made based not only on the current state but also on the predicted state of the near future.

As measures to estimate the path, the environmental load, value, and cost are provided for each stage based on the degradation model of the part as described below.

The probability that the part will take a certain path is also provided. The probability of following a path in the expanded life cycle is derived based on user preference. We assume that the user has certain preferences for the management of parts. Some may prefer lower cost options, some may prefer higher value options, and others may prefer to maintain a low environmental load. Based on these user preferences, probability is assigned to each path.

The derivation method of these probabilities is still to be developed. The probabilities should be determined both by user's preference and degradation of the part. The user's preference may be estimated through the declaration made by the users as well as through their captured behavior.

Based on these measures, the total performance index (TPI) [11] is derived for the evaluation of a stage. TPI provides a proper evaluation of the performance of a part throughout its life cycle by balancing its value, environmental load and costs and is given in the following equation.

$$TPI = \frac{value}{\sqrt{cost \times environmental\ load}} \qquad (1)$$

A large TPI indicates that the value is high compared to the environmental load and cost. The expected TPI of the stage is calculated using equation (1) based on the expected value, the expected cost and the expected environmental load. A part agent can then propose to the user a choice of life cycle with the highest expected value.

3.4 Degradation of a part

To create a simulation to estimate the future state of a part, we assume that a part deteriorates with operational time. Our degradation model of the part is shown in Figure 4. The value of the part decreases with the time spent in use. When the part is repaired, some value is recovered. When the value dips below a threshold, disposal is recommended for the part.

In our simulation, described in Section 4, the maximum value is given to a part when it is newly produced. The value is reduced in the 'use' stage. It is increased in the 'repair' stage by a certain percentage (or to the maximum if the increase exceeds the maximum). Any part is sent to the 'dispose' stage when its value drops below a threshold.

We assume that the degradation of the value of the part affects its cost and environmental load as shown in equations (2) and (3) respectively.

$$cost = fcost(value) \qquad (2)$$

$$environmental\ load = fenv(value) \qquad (3)$$

Functions *fcost*() and *fenv*() may differ depending on the part type and may have additional parameters relating to usage and environment. In this paper, we assume simple linear functions as shown in equations (4) and (5).

$$fcost(value) = -A_{cost} \times value + B_{cost} \qquad (4)$$

$$fenv(value) = -A_{env} \times value + B_{env} \qquad (5)$$

where A_{cost}, B_{cost}, A_{env}, and B_{env} are positive coefficients depending on the type of part.

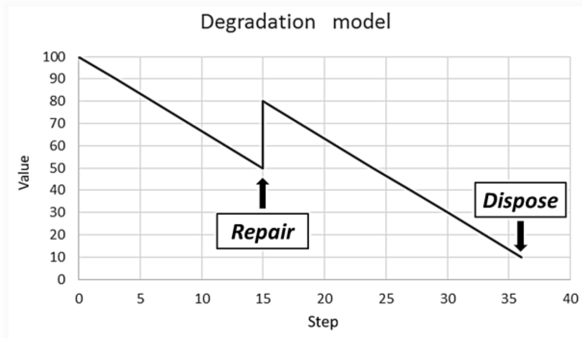


Figure 4: Degradation model.

3.5 Estimation of a path

Based on the equations derived from the models described above, expected value, cost, and environmental load are calculated as shown in equation (6) to estimate life cycle paths. The expected value of an expanded path is obtained by multiplying the probability of the path *Prob*(Ex*Path*) and the expected value of the expanded stage connected from the expanded path *ExpVal*(Ex*Stage*|*From*(Ex*Path*)). The expected value of an expanded stage *ExpVal*(Ex*Stage*) is calculated by summing up the expected values of all expanded paths starting from the expanded stage.

$$ExpVal(ExStage) = \sum_{ExPath|From(ExStage)} \{Prob(ExPath) \cdot ExpVal(ExStage|From(ExPath))\} \qquad (6)$$

Note that the probabilities of all expanded paths starting from an expanded stage sums to one. These probabilities are derived from user's preference as described in 3.3. Further, note that equation (6) is recursively defined. In other words, to obtain the expected value of an expanded stage, it is necessary to calculate the expected value of other expanded stages. To avoid an infinite series of calculations, a maximum depth of calculation is given for the system. For the expected value of an expanded stage at the termination level, the value of the expanded stage is used instead of calculating the expected value obtained from equation (6).

The part agent performs this simulation at each time step in order to decide the appropriate path to take.

4 IMPLEMENTATION OF THE SYSTEM

Figure 5 shows how a part agent decides the appropriate actions for a corresponding part. The part agent has life cycle information of the part and its current state, including the life cycle stage. The part agent expands the life cycle to compose an expanded life cycle, starting at the current stage for a specified time step. Detailed information on expanded stages and paths such as deterioration, cost, and environmental load are calculated using the corresponding models described in the earlier and current states. Simulation is performed using this expanded life cycle. The part agent generates advice to the user based on the simulation result.

A prototype system of a part agent performing this process at each time step was implemented using the object-oriented programming language Java.

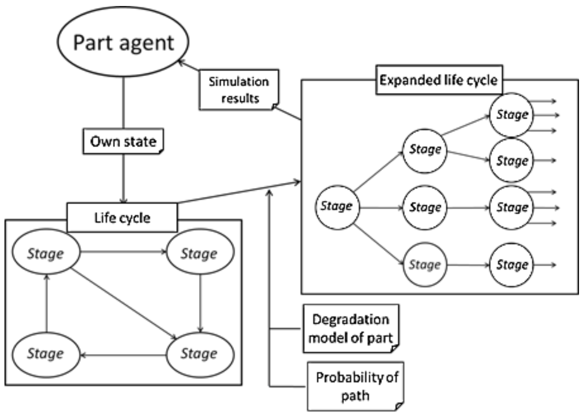


Figure 5: The part agent process used to decide appropriate actions for the corresponding part.

5 LIFE CYCLE SIMULATION

5.1 Simulation process

We developed a prototype simulation for the estimation of candidate paths.

A simple life cycle, shown in Figure 6, is defined for the simulation consisting of six stages: the 'produce' stage, 'sell' stage, 'use' stage, 'repair' stage, 'refurbish' stage, and 'dispose' stage. Paths connecting these stages are also defined: 'produce to sell,' 'sell to use,' 'use to repair,' 'repair to use,' 'use to refurbish,' 'refurbish to sell,' 'use to dispose,' 'produce to produce,' 'sell to sell,' 'use to use,' 'repair to repair,' and 'refurbish to refurbish.'

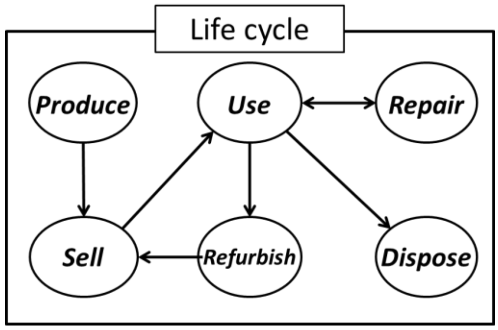


Figure 6: A simple life cycle.

Figure 7 shows the expanded life cycle generated from the simple life cycle in Figure 6 when the part is in the 'use' stage.

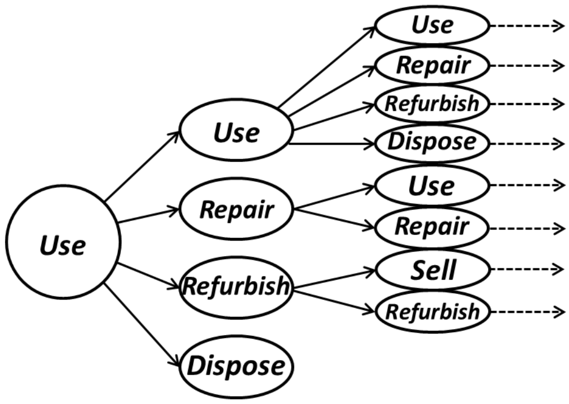


Figure 7: Expanded life cycle.

The properties of parts are updated in the stages as shown in Table 1. Note that we took a simple assumption where the cost and the environmental load depend on the value that degrades with time. When the part is in 'use' stage, its value decreases to 90% of the value of the former time step as shown in the table. The value is assumed as 100 when it is newly produced. We also assume that the probability of paths from 'use' stage to 'repair' stage, 'refurbish' stage and 'dispose' stage changes as the degradation of the value as shown in Table 2. We provide other paths to different stages with probability of 1.0 and those back to own stages with 0.0.

Table 1: Properties of stages

	Value	Cost	Environmental load
Produce	100	100	50
Sell	value	50	20
Use	0.9×value	11−0.1×value	11−0.1×value
Repair	1.2×value	50−0.19×value	30
Refurbish	1.1×value	50−0.1×value	20
Dispose	0.3×value	30	150

Table 2: Probabilities of paths from ‘use’ stage

From \ To	Use	Repair	Refurbish	Dispose
Use	$\frac{value-1}{100}$	$\frac{100-value}{200}$	$\frac{100-value}{200}$	0.01

As an example, Figure 8 shows a result of the expected cost calculated with our method of simulation. Circles represent the stages and squares represent the paths. The number in a circle shows the cost of the stage itself calculated based on the parameters in Table 1 with the expected cost of all the branches starting from that stage shown in parentheses. The number in a square shows the probability the path will be selected. Dotted arrows starting from Use (Start) show the options at the stage.

In this simple example, the simulation is run for only one step to confirm the calculation process. For example, the expected cost of the ‘use’ stage in the middle is calculated using only the costs of the four stages that branch from it. The cost of the ‘use’ stage in the middle is calculated as 1.0 using Table 1 with the current value of 100. For the stages in the right of the middle ‘use’ stage, the value of the middle ‘use’ stage decreases to 90 and hence, the cost in right ‘use’ stage is estimated as 2.0, the cost in right ‘repair’ stage as 32.9, and so on, using the similar calculation. Using these estimated costs and taking into account the probabilities of the corresponding paths, the total expected cost for all the branches starting this ‘use’ stage is calculated as shown in the following equation.

$$ExpC(Middle\,Use) = 1.0 + (2.0 \times 0.89) + (32.9 \times 0.05) + (41.0 \times 0.05) + (30.0 \times 0.01) = 1.0 + (5.72) = 6.72 \quad (7)$$

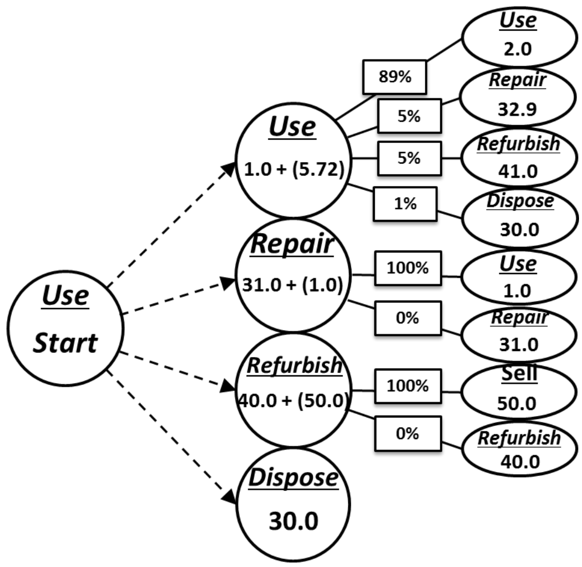


Figure 8: Calculated results of the expected cost.

Similarly, the expected environmental loads and value are also calculated. The expected TPI is calculated based on the estimation of the expected value, cost and environmental load as described in 3.3.

5.2 Simulation results

To evaluate our method of prediction, a part agent was run for 10 steps choosing an appropriate stage in each step.

As described above, the part agent calculates expected value, cost, environmental value and TPI for each candidate stage. It takes the path to the stage with the best expectation that is the highest value, the lowest cost, the lowest environmental value or the highest TPI according to the user’s preference. The user is assumed to accept every advice from the part agent in this simulation.

We compared two cases of the simulation, one using our method and the other with randomly selected path. The results are shown in Figure 9 and 10. The black lines show the interested values for the paths selected by the part agent and the gray lines show those for the paths randomly selected. Figure 9 shows the value of the part and the stages its part agent has selected when the agent selects the paths with the highest expected value. In contrast to the case where the path was selected randomly, the selections by the part agent mostly result in higher value.

Figure 10 shows the TPI when the part agent chose stages with the highest TPI. The fluctuation is due to the part agent behavior based on its prediction. It foresees the higher TPI of future stages after the lower TPI of next stage.

The average TPI in 8 steps for the parts using our method and for the parts selected randomly were 28.50 and 26.16, respectively. In other words, the average TPI for our method was 108% of that obtained by random selection. Furthermore, the part following the part agent selection survived 10 steps whereas the part in random selection reached ‘dispose’ stage and terminated its life in 8 steps.

We believe that, though still premature, the results show potential for the effectiveness of our system.

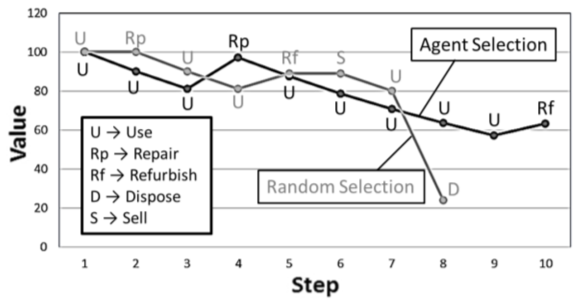


Figure 9: Simulation result when the part agent chose the path with the highest value.

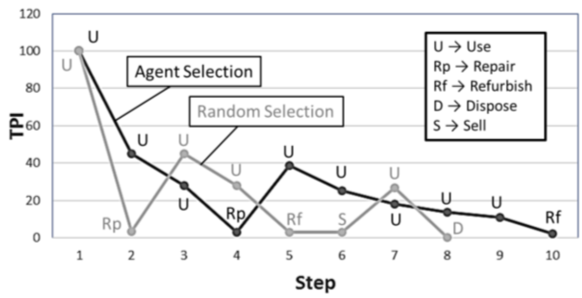


Figure 10: Simulation result when the part agent chose the path with the highest TPI.

6 DISCUSSION

The simulation result shows that the estimation of values in the near future would be an effective tool for generating advice.

The remaining issues and future prospects include

- creating a more realistic degradation model for parts,
- estimating the probability of paths,
- communicating with multiple agents, and
- performing simulations for assembly consisting of part agents.

As we described in Section 3.4, the degradation model for parts would not be as simple as given in Figure 4. Parts may deteriorate suddenly after exceeding a certain usage time, or may not significantly degrade for a long period. We need to create a deterioration model that considers the characteristics of each part.

The probability a path will be taken depends on the preference of the user, and the deterioration model of the part must also be considered. We need to calculate the probability of a path based on this information.

A single part is dealt with in this paper. However, required information may change because of the mutual effects of other parts and part agents. To solve this issue, appropriate communication will be required among part agents.

A product is composed of multiple parts. Therefore the simulation should deal with multiple part agents. Deterioration of a part affects other parts in the same assembly. Parts are not only repaired but also replaced. These issues need to be solved when assemblies are considered.

7 CONCLUSION

In this paper, we proposed a part agent to promote the reuse of parts. To overcome the uncertainty that cannot be predicted in the design phase, a fundamental mechanism was proposed to select the best life cycle path based on life cycle information. Future work is also discussed.

8 ACKNOWLEDGEMENTS

This research is partly funded by Grants-in-Aid for Scientific Research, the Ministry of Education, Culture, Sports, Science and Technology, Japan.

9 REFERENCES

[1] Hauschild, M., Jeswiet, J., Alting, L., 2005, From Life Cycle Assessment to Sustainable Production: Status and Perspectives, Annals of CIRP, 54/2:535–555.

[2] Sakai, K., 2007, Ricoh's Approach to Product Life Cycle Management and Technology Development, Proceedings of the 14th CIRP Conference on Life Cycle Engineering: 5-9.

[3] Borriello, G., 2005, RFID: Tagging the World, Communications of the ACM, 44/9:34–37.

[4] Hitachi Ltd., Hitachi Develops a New RFID with Embedded Antenna µ-Chip, http://www.hitachi.com/New/cnews/030902.html (accessed on 9 April, 2013).

[5] Hiraoka, H., Ito, K., Nishida, K., Horii, K., Shigeji, H., 2011, Development of Part Agents for the Promotion of Reuse of Parts through Experiment and Simulation, Glocalized Solutions for Sustainability in Manufacturing, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering: 419-424.

[6] Kunii, E., Fukushige, S., Umeda, Y., 2011, Development of CAD System for Life Cycle Scenario-Based Product Design, Glocalized Solutions for Sustainability in Manufacturing, Proc. of the 18th CIRP International Conference on Life Cycle Engineering: 118-123.

[7] Wada, H., Kishita, Y., Mizuno, Y., Hirosaki, M., Fukushige, S. Umeda, Y., 2011, Proposal of a Design Support Method for Sustainability Scenarios 1st Report: Designing Forecasting Scenarios, Glocalized Solutions for Sustainability in Manufacturing, Proc. of the 18th CIRP International Conference on Life Cycle Engineering:189-194.

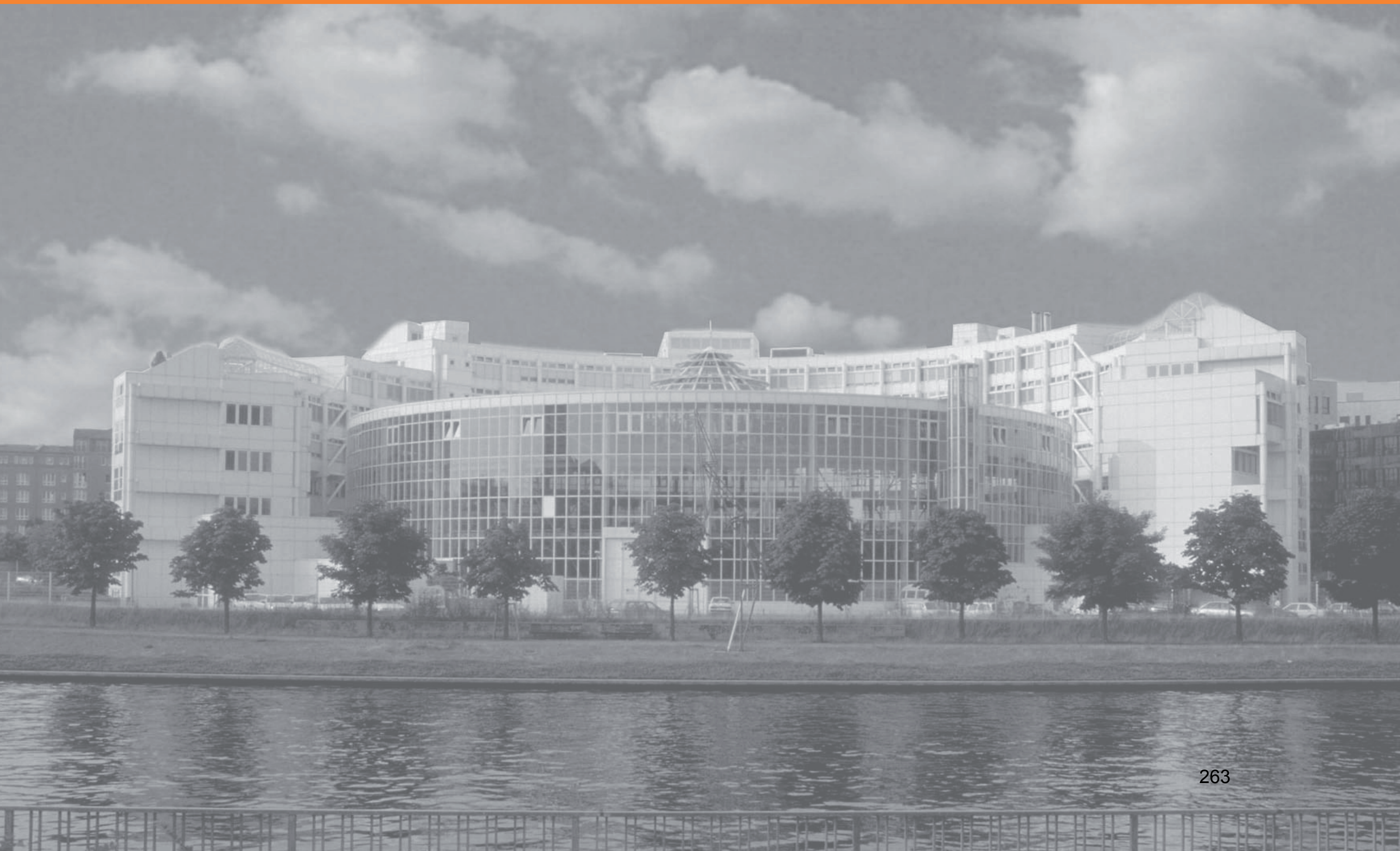
[8] Komoto, H., Tomiyama, T., Nagel, M., Silvester, S., Brezet, H., 2005, Life Cycle Simulation for Analyzing Product Service Systems, Proc. of EcoDesign 2005: 2B-1-2F.

[9] Komoto, H., Masui, K., Kondoh, S., 2012, A simulation method of dynamic systems applied to backcasting scenario design, The Philosopher's Stone for Sustainability, Proc. of the 4th CIRP International Conference on Industrial Product-Service Systems: 333-338.

[10] Jun, H. B., Kiritsis, D., Xirouchakis, P., 2007, Research Issues on Closed-Loop PLM, Computers in Industry 58: 855–868.

[11] Kondo, S., Masui, K., Mishima, N.,Matsumoto, M., 2008, Total performance analysis of product life cycle considering the uncertainties in product-use stage, Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses: 371-376.

Session 8
Process



8.1 HPC for improved efficiency on standard machine tools by using new fluid-driven spindles

A. Schubert [1], O. Harpaz [2], B. Books [2], U. Eckert [1], R. Wertheim [1]

[1] Fraunhofer IWU, Reichenhainer Str. 88, 09126 Chemnitz, Germany

[2] Colibri Spindles Ltd., Lavon Industrial Park, M.P. Bikat Bet Hakerem 25127, Israel

Abstract

The use of fluid-driven spindles is well known for machining various components, but not in real metal cutting. Machining of larger precision components as prototypes, tools and dies requires the use of relatively large machine tools and high-performance spindles. Usually these are mechanical spindles with relatively high power, displaying a rather low maximum speed of approximately 15,000 rpm. However, in semi-finishing and finishing with HPC conditions and in micro machining, the required rotation speeds are higher and the required power is lower.

This paper presents sustainability and efficiency using fluid-driven spindles for HPC on standard machine tools with small tool diameters and rotation speeds of up to 90,000 rpm using air and 30,000 rpm using the coolant flow. The fluid-driven spindle leads to a significant widening of the application range of larger machine tools and to an improvement of productivity by higher efficiency and faster tool- and spindle change, respectively.

Keywords:

HPC; Cutting; Tools; Spindle

1 INTRODUCTION

Machining of large precision components for the dies and molds industry, for aerospace applications or for the machine tool industry requires the use of large machine tools with relatively high power spindles but with relatively low to medium rotation speeds of up to 15,000 rpm. A growing demand for micro structures, engravings, surface modifications or micro-functional geometries can be observed for many of the machined parts. On the one hand, using the heavy duty spindles for this range of applications is difficult and uneconomic due to the lower rotation speed and limited performance. On the other hand, using an additional micromachining center with small working area does not allow heavier parts and is uneconomic because of high investment cost, short productive time and lower efficiency.

The use of an additional fluid-driven spindle on the same heavy duty machine utilizes the standard air supply or the coolant supply system of the machine, improving efficiency, costnd saves additional machining equipment.

The current investigation presents the theoretical background, the properties of the fluid-driven spindles and the machining performance of the air and coolant-driven spindles.

2 COMPARISON OF ELECTRICAL, MECHANICAL AND FLUID-DRIVEN SPINDLES

Fig. 1 shows a comparison of various spindle types for rotation speed enhancement which can be used in combination with the machine tool main spindle. While the electrically and mechanically driven spindles require separate energy sources for the spindle and the coolant supply with or without using a speed increaser, the new unique fluid-driven spindle is rotating and cooling the machining area with a single energy source. The new fluid-driven spindles can be mounted on the standard machine tool spindle with minimal setup time, can be gripped automatically in the tool changer and stored in the tool magazine. Flushing can be carried out for the various spindle concepts through the main spindle or externally.

The air-driven spindle can provide high rotational speed, tested here with up to 90,000 rpm and small torque and a coolant spindle with up to 30,000 rpm.

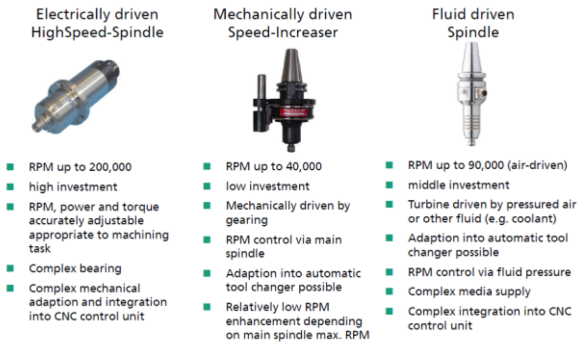


Figure 1: Comparison of spindle solutions for RPM enhancement which are adaptable in addition to the machine tool main spindle.

Fig.2 illustrates the cross section of the air- and the coolant-driven spindle concept (A) and (B), including a shank for clamping, a turbine for actuation, bearings, housing and the medium supply channels. The design enables the use of a wide range of replaceable tools clamped directly into the

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

spindle as well as the utilization of standard tool clamping devices.

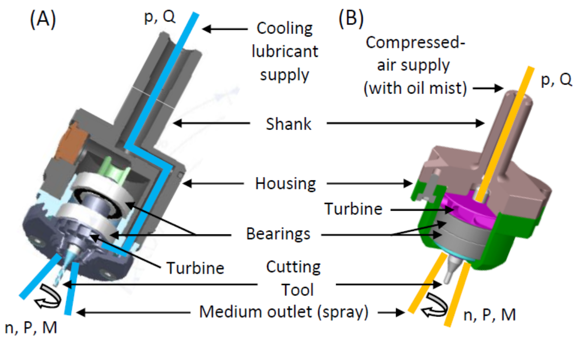


Figure 2: Cross section of the coolant-driven (A) and the air-driven (B) spindle concept.

In order to enable flexibility and to guarantee reliability and repeatability during machining with this spindle concept the design includes some unique features. The spindle shank can be clamped as a unit into any available standard main spindle device of the machine tool, or it can be mounted parallel to the main spindle. By selecting and controlling the air or coolant supply, especially as regards pressure (p) and flow rate (Q), it is possible to control or to achieve nearly constant rotation speed (n), torque (M) and power output (P).

3 THE AIR-DRIVEN SPINDLE

The air-driven spindle (Fig. 2 B) offers high RPM of up to 90,000 min-1, but relatively low power output of less than 50W. Therefore, the actuation concept is only applicable for very small tool diameters and micromachining processes. Due to the limited torque, further finishing operations of high performance cutting with small tool diameters cannot be realized with the air-driven spindle concept. The following chapters 3.1 and 3.2 describe some fundamental investigations using the air-driven spindle concept.

3.1 Air Pressure and Rotation Speed

The investigations of the air-driven spindles were carried out with various exchangeable heads, including integrated cutting tools:

- Two exchangeable heads with ∅ of 0.5mm - Solid carbide end mills with 2 flutes and a helix of 30°. One of them with easily rotating spindle due to larger bearing clearance (approximately 40µm), and the other one nearly without bearing clearance (approximately 4µm)
- Two exchangeable heads with ∅ of 1.0mm - Solid carbide short ball nose end mills with 2 flutes, helix of 30° and nearly without bearing clearance (approximately 4µm).

The rotation speed was checked in comparison with a spindle of a Kugler 5-axis machining center. A calibration test was realized with the fluid-driven spindle with an air pressure of 5.5 bar to prepare the RPM control unit for the repeatable rating tests of the new spindle. Further investigations were realized without real cutting to define the characteristics of the above described spindles with the various exchangeable heads. It could be detected that without machining a 7 bar air inlet pressure is required in order to reach 120,000 RPM. Fig. 3 presents the progression of rotation speed and air-flow rate for the four exchangeable heads as a function of the air inlet pressure. It could be found that the flow rate behavior for all four tested tools as a function of the air pressure does not depend on the bearing clearance or on the tool diameter. It could also be shown that the run out is almost independent of the flow rate or air pressure.

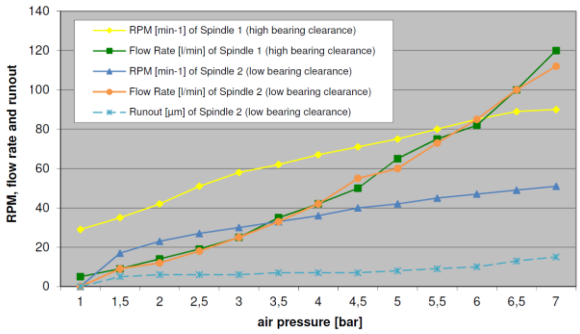


Figure 3: Rotation speed, flow rate and runout as a function of air inlet pressure and bearing clearance.

It can be concluded that an easy rotating spindle 1 with a clearance of 40µm can reach 90,000 RPM, while due to a smaller tolerance of 4µm and a higher resistance of spindle 2 the max. rotation speed is only 50,000 RPM. Therefore, an optimization process of the bearing design is required for optimal performance of the air-driven spindle.

3.2 Machining Conditions and Performance

The cutting tests were carried out with a ∅ of 0.5mm - Solid carbide end mills with 2 flutes and a helix angle of 30°. The rotation speed was 45,000 min-1, which is equivalent to vc = 70m/min. The feed per tooth was 2µm, which is equivalent to a table speed of vf = 180mm/min. The depth of cut a_p varied between 0.01mm and 0.4mm and the width of cut a_e varied between 0.005mm and 0.025mm.

The overview of the different geometrical machined shapes are shown in Fig. 4 (a to e).The selected finishing conditions are indicated below for each of the machined shapes.

a) Finishing a fin in down milling with a_p = 0.2mm and a_e = 0.025mm with overall 4 steps a_e and a total width of 0.1mm. High accuracy was achieved with relatively small tool deflection. Fin height was 198µm and width was 208µm. A good perpendicularity with a width difference of +8µm could be reached. The surface quality was evaluated using a confocal microscope and the surface quality results are at bottom Rz = 1.1µm and at flank Rz = 2.3µm.

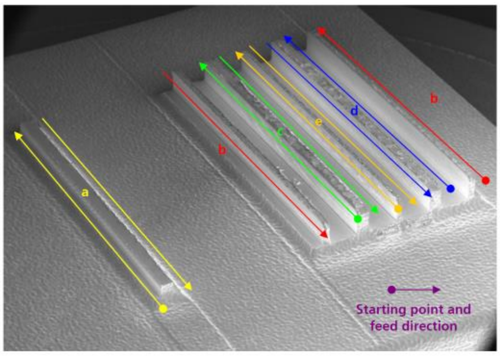


Fig. 4: Machining order of different geometrical shapes with different cutting conditions using the air-driven spindle.

b) Finishing a flank in up milling with a higher load of a_p = 0.4mm and a_e = 0.025mm with 5 steps of a_e overall and a total width of 0.125mm. Good accuracy was reached with a measured deviation in width of -6µm compared to the targeted value. However, a small deflection of the fin was detected after the last cutting step no. 5, probably due to the increased cutting depth of 0.4mm. The surface quality showed only a small deviation in comparison to the results in machining step a) with the smaller depth of cut a_p.

c) Roughing a fin from the solid in down milling with a_p = 0.01mm and a_e = 0.5mm with 40 steps of a_p overall and a total cutting depth of 0.4mm. A comparatively good geometrical accuracy was achieved with a width deviation of +10µm and a height deviation of -12µm compared to the reference. The deviation in height could be explained by tool wear.

d) Roughing a fin from the solid in up milling with a_p = 0.01mm and a_e = 0.5mm with 40 steps of a_p overall and a total cutting depth of 0.4mm. A comparatively good geometrical accuracy was achieved with a width deviation of +7µm and a height deviation of -15µm compared to reference. The increasing deviation in height could be explained by tool wear.

e) Finishing a 0.4x0.050 mm fin, shown in Fig. 5, in down milling with a_p = 0.4mm and a_e = 0.005mm, including a burr removal at zero level before finishing the flank with 5 steps of a_e overall and a total cutting width of 0.025mm.

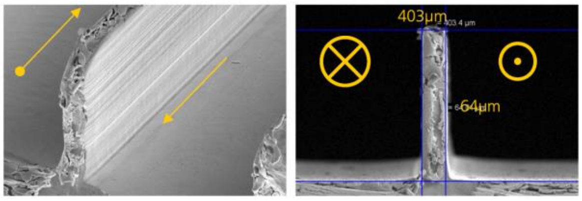


Fig. 5: SEM pictures of the finished fin (e) with the new air-driven spindle under finishing conditions.

Acceptable geometrical accuracy was achieved with a maximum width deviation of +14µm and a height deviation of +3µm compared to the nominal reference values.

3.3 Conclusion of Investigations of the Air-Driven Spindle

Good RPM-stability (after running-in) is achievable under constant air conditions (pressure, oil mist, flow rate). The use of a MQL system with medium flow rates is difficult to adjust. Consistently typical results for accuracy and surface quality could be achieved during the different machining operations. The tool wear was inconspicuous for the preliminary tests and no thermal effects were detectable during operating of the new air-driven spindle. The temperature of the spindle was nearly constant during the machining operations. Only some vibrations were detectable during cutting, but obviously without effecting surface quality.

It is very interesting and easy to use this spindle concept with limited power and torque, for example for parallel HSC-operations and micromachining processes. It has a high potential for use on conventional machine tools, depending on machine stability.

Detailed characteristics and operating behavior of the new air spindle concept have to be investigated, and it is required to check limits of the new spindle concept under various influencing variables. In comparison to the air spindle, higher reliability and repeatability can be expected with the coolant-driven spindle.

4 THE COOLANT-DRIVEN SPINDLE

4.1 Basic Function of the Coolant-Driven Turbine Spindle and Spindle Modifications

During the investigations basic calculations were realized concerning design and dimensions of turbines. The layout and dimensions of both, the turbine blade geometry and the fluid inlet channels, were broadly investigated, calculated and optimized. The theoretical idle RPM, the torque and the power output for different fluid-driven turbine types and geometries were investigated as a function of rotation speed and coolant flow conditions. Analysis of the torque, the loss of RPM and the power output can define an efficiency factor. The results of the theoretical analysis were compared with the results of practical investigations using real fluid-driven turbines [4]. Fig. 6, for example, shows the characteristic behavior of a medium to high power fluid-driven turbine. The diagram describes the calculated deviation of power output and torque as a function of turbine rotation speed. The various graphs present the maximum theoretical power output of the turbine (blue line - A), the increasing losses of power output as a function of increasing turbine speed (red line - B), the resulting turbine power output available for the machining process (green line - C) and the decreasing torque (purple line – D) as a function of increasing turbine speed.

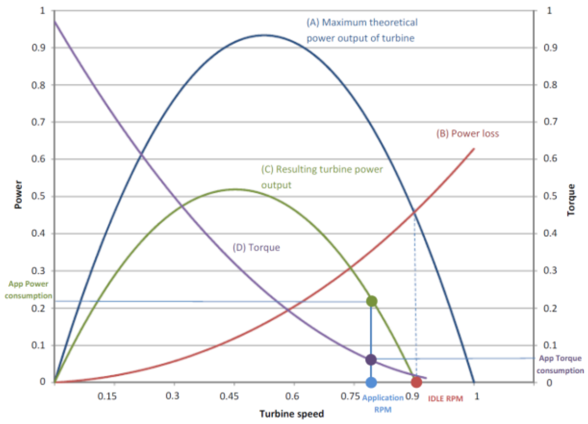


Fig. 6 Characteristic basic behavior of a typical fluid-driven spindle actuated by the cooling flow.

Fig. 6 illustrates that the fluid-driven turbine is limited as regards the available RPM range. In general, the recommended operating range is defined between 65% and 95% of the IDLE rotation speed. Lower speeds are not efficient while higher rotation speed reduces torque and power output significantly. The example indicated in the figure shows that for about 78% of the rotation speed the torque is less than 10% and the resulting power output for cutting is about 22% of the maximum value.

Literature offers similar range maps that describe different turbine types and allow selection of a turbine type and specifications according to the application requirements. The selection depends on fluid inlet pressure (p), flow rate (Q), power output (P) and output rotation speed (n). However, most of these publications refer to significantly larger turbines using higher power [4]. For lower power, as in our case, the theoretical behavior and the experimental characteristics have to be investigated by using various design and geometrical features.

4.2 Design and Features of the Fluid-Driven Spindle

During the investigation the turbine design including fan form, number of blades and fluid inlet/outlet geometry were optimized for maximum efficiency resulting in a unique structure. It was found that the designed and optimized small turbine shown in Fig. 7 (A) deviates far from the commonly accepted structures. Hence, only limited design criteria are known which can be used for the present application. The final fluid-driven spindle used in the investigation and shown in Fig. 7(B) and 7(C) is designed for a power output range of less than 1 kW.

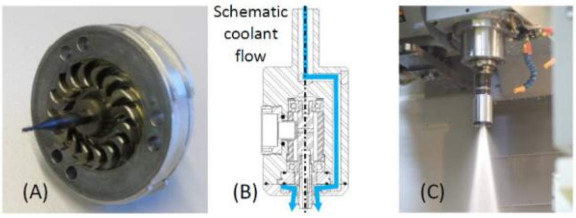


Fig. 7: The turbine fan design (A), cross section of the spindle (B) and the spindle actuated by the cooling lubricant (C)

First the general conditions were investigated for the application of the spindle concept on a machine tool. The concept of the spindle required a supply of cooling lubricant or pressured air through the clamping shank for operating the spindle. Therefore, different interfaces for reliable clamping of the spindle were analyzed. Collet chuck holders or shrink collets are possibilities for a spindle adaption with a standardized tool holder (e.g. HSK63-A). Fig. 8 presents, for example, the second spindle prototype in which the tool is clamped into a holder with shrink collet and also describes the main components of the spindle.

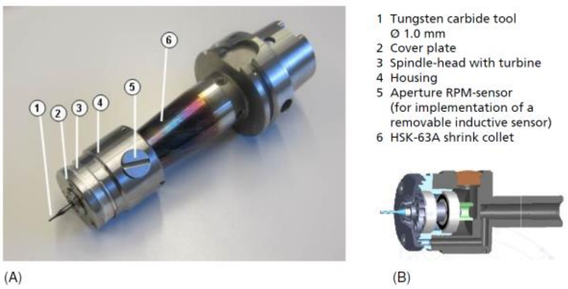


Fig. 8: Overview of the second spindle prototype mounted in holder (A) and cross section view (B).

4.3 The Experimental Setup

Systematic and different investigation steps were carried out for analyzing and rating of the different prototypes of the spindle concept. This analysis mainly included the following points for a comprehensive rating of the spindle concept:

- Rotation speed (RPM) depending on coolant lubricant pressure (pump and spindle)
- Measurement and calculation of power output depending on RPM
- Measurement of cutting forces in comparison with results from other high precision spindles for micromachining
- Measurement of spindle stiffness
- Rating of achievable surface quality and geometrical accuracy
- Design optimization based on measuring results

For example, the evaluation of machining performance was carried out in real cutting tests based on the machining conditions. These tests featured various materials machined by various coated tungsten carbide tools. A special experimental setup was developed to measure the power output and to calculate the torque. Additional measuring methods such as measurements of the cutting forces were used to rate the machining characteristics and performance of the new spindle systems and to give further feedback concerning design and dimensions of the spindles (e.g. for dimensioning the bearings) [5]. A conventional method was tested using a torque measuring shaft device for measuring the values. This torque measuring shaft is problematic at higher RPM and disadvantageous during operations with high torque of inertia. Also the placement of the tested components is difficult without lateral off-set. These problematic facts require the development of a new and improved test setup (Fig. 9) for measuring torque and power output under various load conditions. This new setup is based on a generator (electric motor) which is driven by the spindle concept. The connection is realized with a balanced clutch. A sheet metal is used to avoid mechanical load on the bearings of the generator by high pressure coolant lubricant.

Before any measuring of torque and power output the detection of the characteristic power curve of the electric motor was required for envisaged use as a generator. Therefore the generator (electric motor) was driven by a second identical electric motor while the power input and output was measured with a power measuring device and the characteristic power curve was reproducible documented. The identified characteristic power curve of the electric motor was basically used for further investigations and calculations for rating the spindle.

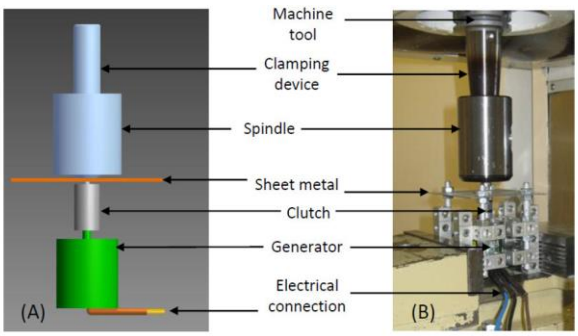


Fig. 9: Newly developed setup for measurement of power output (A) concept (B) implementation into machine tool.

4.4 Features and Performance

In order to simulate different cutting conditions, the equipment was completed with a special setup to stress the spindle with various electrical loads. The following Fig. 10 presents the performance of the spindle concept measured with the load measurement setup. In this case, the power output is presented as a function of rotation speed and coolant pressure at pump.

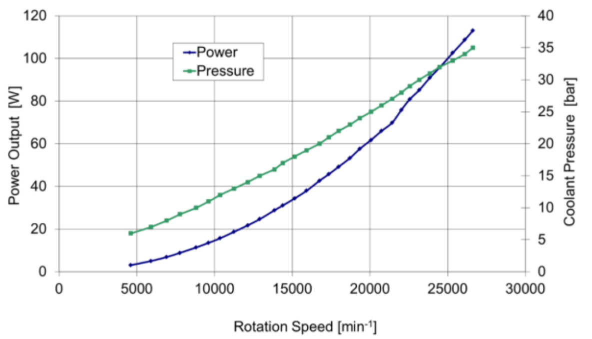


Fig.10: Power output as a function of cooling lubricant pressure (at pump) and rotation speed for the selected spindle design.

In order to further rate the potential and the machining range different machining operations were realized while measuring the cutting forces with a 3-axis dynamometer. Investigations were first carried out on a micromachining center with a conventional HSC spindle and later repeated using the fluid-driven spindle concept to evaluate and compare the test results. Simple machining operations including slotting, shouldering and drilling of steel and aluminum were carried out and investigated using numerous different cutting parameters. A good correlation of the cutting forces could be determined between standard micromachining and machining with the fluid-driven spindle. The effective cutting forces are quite small and unproblematic for machining operations. The maximum forces could reach high values, so it is important to use an adapted machining strategy to avoid tool breakage or higher RPM loss, especially at the start of cut or in jump down applications. Results of cutting force measurement with the fluid-driven spindle are shown in Fig. 11. The diagram presents the maximum cutting forces as a function of feed rate.

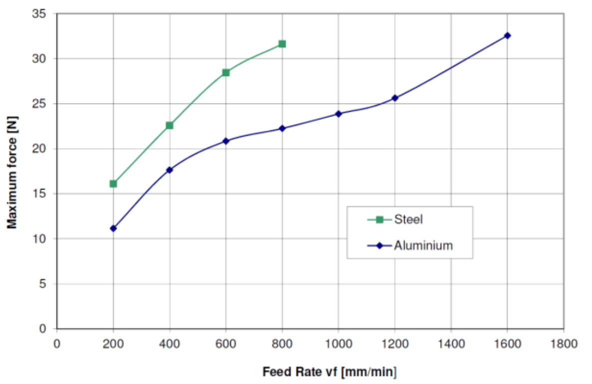


Fig.11: Effective cutting forces as a function of feed rate in full slotting with ∅ 3mm tool.

The surface quality of the test samples was analyzed in machining steel and aluminum with different machining conditions. A confocal white light microscope (optical system) was used to rate the surface quality and to find a correlation to the used cutting parameters. A comparison of the surface quality with the values achieved using the conventional machining showed identical results. However, the use of the new spindle concept requires an adapted strategy and parameters because of some differences in spindle characteristics. The surface quality of steel is better than aluminum. The depth of cut influences the surface quality in larger values due to deflection, while the lower quality in higher feed rates is expected due to larger tooth loads.

Another important rating criterion is the detection of the application range of the spindle concept. It indicates the limits for the achievable and useful range of rotation speed and corresponding to the machining power. Analyzing the machining process showed multiple factors for power losses: friction in the bearings, shaft misalignment as well as friction between the fluid and the rotating parts. Reducing power losses may result in significantly higher machining power, higher idle RPM and an improved efficiency factor. During the investigation the system was analyzed and modified to minimize friction and power losses, which are the main reason for the reduction of rotation speed of spindle under external load. It is important to calculate and define the minimum spindle speed and the cutting parameters in order to avoid overload on the cutting tool. High table feeds and larger depths of cut at low rotation speeds may result in high loads on the cutting edge and breakage. Fig. 12 illustrates the decrease of rotation speed as a function of cutting depth a_p when machining aluminum and steel.

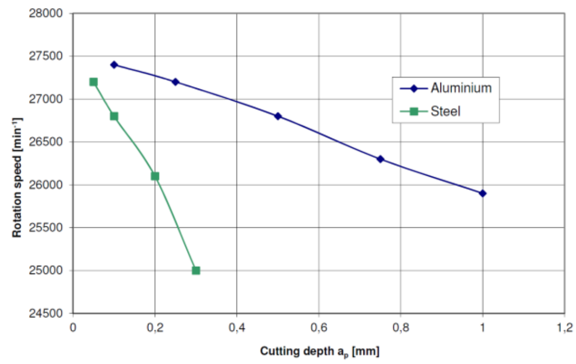


Fig. 12: Decrease of rotation speed as a function of cutting depth in milling aluminum and steel

All these investigation steps for rating the characteristics and performance of the spindle system provide important feedback to improve design, dimensions and machining behavior of the different prototypes [6].

4.5 Machining Results

Machining tests were carried out on cold working steel 1.2379, using a standard tungsten carbide end mill with ∅ 1.0mm in face milling of an area of 50mm x 50mm. The tests were carried out at a cutting speed of 75m/min and feed rate of vf = 300 mm/min up to a removal volume of 125mm³. The final measured surface quality was very high, reaching Rz = 1.3µm and Ra = 0.2µm. Investigation results showing the microstructure and surface quality of a machined cold working steel 1.2379 are presented in Fig. 13.

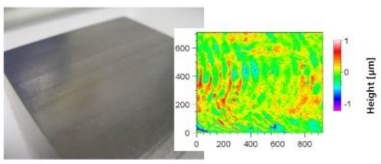
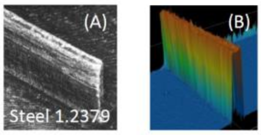


Fig. 13: Results of face milling in 1.2379.

Following these positive test results, further milling operations were carried out with various cutting parameters, e.g.

operations of slotting and shouldering of steel and aluminum. Machining of microstructure elements such as fins with a width of 50µm and a height-aspect ratio of 10 as shown for the air spindle can be carried out with high efficiency (Fig. 14). The geometrical and shape accuracy such as flatness (1.8µm), parallelism (2.7µm) or thickness and height are excellent and the surface finish was very good (Rz = 2.3µm), even at the bottom of the machined part, presented in table in Fig. 14 (B).



Rating criteria	Results
Straightness deviation	1.8µm
Parallelism	2.7µm
Geometrical accuracy width	< 9µm
Geometrical accuracy heigth	< 3µm
Surface quality Rz (bottom)	2.3µm

Fig.14: Machined fin width 50 µm and height 500 µm (A), rating by 3D laser scanning microscope and results (B).

5 INDUSTRIAL APPLICATIONS

A machining example of a real component is shown in Fig. 14, using the fluid-driven spindle concept and the main machine spindle to demonstrate the technological potential of this solution. The machining parameters achievable with the new spindle compared with those of a conventional main spindle are presented in the table in Fig. 15. The new fluid-driven spindle reduces the machining time by 75% and improves the cost per workpiece, resulting in saving $44 per part.

	Main spindle	Fluid-driven spindle
Tool diameter [mm]	1	1
Spindle speed [min-1]	9,000	35,600
Cutting speed [m/min]	28	112
Feed per tooth [mm/tooth]	0.016	0.016
Table feed [mm/min]	288	1,140
Machining time per part [min]	60	13

Fig. 15: Machining results using the main machine spindle and the coolant-driven spindle for cutting a turbine made of stainless steel SAE 303 (1.4305).

Another case study describes the machining operations for roughing and finishing of an injection mold component using the fluid-driven spindle in comparison to the machine tool main spindle. During roughing the machining time could be reduced only by 18%, in comparison to roughing with the machine tool main spindle, higher cutting speeds allows for higher feed rates and optimized machining parameters in the finish milling process.

It could be impressively demonstrated that the use of the fluid-driven spindle improves the efficiency of the machining process by reducing machining time. Furthermore, the achievable surface quality while finishing under High Performance Cutting conditions can save an additional polishing process of the mold component.

6 SUMMARY

The test results with different prototypes of the spindle concept showed high performance of this new and innovative solution. It was demonstrated that the new concept is functioning successfully when using the flushing system of the machine tool at a wide range of coolant inlet pressure (6-35bar). Moreover, it can be concluded that an integration of a control device for pressure and flow rate of the cooling lubricant can control the rotation speed (RPM) and power of the new spindle during operation.

A uniquely developed experimental setup made it possible to measure forces, power output and to calculate torque. Special measuring methods such as acoustic emission or measuring of cutting forces were used to rate the characteristics and performance of the spindle system and to give feedback concerning design and dimensions of the spindles.

The new and innovative spindle concept used in micromachining and finishing on conventional machine tools achieved high performance, good tool life and high surface quality. Furthermore, the new spindle concept improved efficiency and performance on CNC, on parallel kinematic machines and other machine tools, and reduced the cost of investment.

The project enabled to develop, to investigate and to define the machining conditions and performance of a complete new spindle concept.

More investigations should be carried out to explore the control of speed and fluid flow parameters. The efficiency and energy balance as well as saving of resources should be included in the next development step.

7 REFERENCES

[1] Schubert, A., Schneider, J., Eckert, U.: Influence of special milling strategies on accuracy and surface quality of microstructured forms and prototypes. In: Proceedings of the 3rd International CIRP HPC Conference, Volume I-II, Dublin 2008, S. 131-140.

[2] http://www.eurekanetwork.org/project/-/id/5873

[3] Wertheim, R., Yitzhak, O.: SpinTool - the Spindle - Tool - System. Technical report at STC C meeting, 59th CIRP GA, Boston 8/2009.

[4] Husain, Z., Abdullah, Z., Alimuddin, Z.: Basic Fluid Mechanics and Hydraulic Machines. CRC Press Taylor & Francis Group 2008

[5] Harpaz, O., Books, B., Schwaar, M., Schubert, A., Eckert, U.: Parallel High Speed Machining with a New Additional HSC Spindle for Machine Tools. In: Proceedings of the 5th CIRP Conference on High Performance Cutting, Zurich 2012

[6] Neugebauer, R., Drossel, W., Wertheim, R., Hochmuth, C., Dix, M.: Resources and Energy Efficiency in Machining Using High-Performance and Hybrid Processes. In: Proceedings of the 5th CIRP Conference on High Performance Cutting, Zurich 2012

8.2 Finite element modeling of laser assisted friction stir welding of carbon steels for enhanced sustainability of welded joints

A. H. Kheireddine, A. H. Ammouri, R. F. Hamade

Department of Mechanical Engineering, American University of Beirut (AUB), Beirut, Lebanon

Abstract

In Friction stir welding (FSW) of carbon steels, process parameters must be set to avoid defects such as warm holes. Proper selection of process parameters also affects the final grain microstructure and phase transformations and, ultimately, the weld's mechanical properties. Process parameters, including laser-assisted heating, of AISI 1045 carbon steel were investigated via a 3D finite element method (FEM) model. The laser action was modeled as heat source with constant flux. The simulation findings favorably agree with experiments reported in the literature and suggesting that with laser-assisted-FSW welding can be performed at higher traverse speeds (400 vs. 100 mm/min) while maintaining defect free weld. Also, evolved phase transformations are predicted across the weld geometry as time progresses. Such findings will help in the prediction of sound welding parameters and in estimating the mechanical properties of the various regions of the weld leading to more sustainable joints.

Keywords:
FEM; Simulations, Friction stir welding; Laser.

1 INTRODUCTION

Friction stir welding (FSW) is a solid state joining process that utilizes a rapidly-rotating, high strength steel tool in the form of a pin inserted along the weld steam to join similar or dissimilar metals. Known problems associated with friction stir welding (FSW) may be alleviated by the proper selection of process parameters leading to more sustainable processing and to enhanced welded joints. Such parameters include tool feed, spindle speed, tool geometry, tool tilt angle, and in-process cooling or heating. The proper selection of such factors is a key for achieving defect-free welds by avoiding defects such as warm holes and voids. Furthermore, achieving desirable grain size at the weld as well as the final phases also results from the combination of the process parameters which must be carefully defined in order to achieve target results.

FSW is considered a hot-working process in which massive plastic deformation occurs through the rotating pin without subjecting the workpiece to any form of induced heating or melting. Such deformation gives rise to a thermomechanically-affected rejoin (TMAZ) and a heat-affected zone (HAZ) [1]. During the welding process, the material is wiped from the front side of the pin onto the back side in a helical motion within the stir zone [2]. Among the advantages of Friction stir welding is the ability of this technique to efficiently control the cooling rate and peak temperature by varying the speed of the rotating pin [3]. FSW is used in joining metals of poor weldability and in many green applications [4]. Friction stir welding is heavily used in the aerospace industry to join, for example, high strength aluminum alloys that are hard to weld using traditional welding techniques. For steel and other high-temperature materials, the application of FSW is limited to the presence of suitable tools that can operate in the temperature range of 1000 to 1200 °C [5]. This is due to the fact that the heat produced by stirring and friction may not be sufficient to soften the material around the rotating tool. Therefore, it is important to select tool materials with good wear resistance and toughness at temperatures of 1000°C or higher [4]. However, in the past few years, studies have reported to the effect that FSW is capable of achieving grain improvements in the stir zone in steels similar to those observed in light metals such as aluminum. A number of studies that tackle microstructural changes during FSW have been conducted to examine the influence of the welding parameters on material flow and the shape of the interface between the various zones. One such study [6] modeled friction stir welding of stainless steel (304L) utilizing the finite element method (FEM) and using an Eulerian formulation with coupled viscoplastic flow and heat transfer around the tool pin. Some of the findings were that: higher temperatures on the advancing side compared to the retreating side, higher strength in the weld zone compared to the base material, harder friction stirred zones compared to the unreformed base metals, highest effective stress in the stirred zone, more anisotropy in the material near the friction stirred zone than the material passing farther from the tool pin. The microstructure and mechanical properties of welded joints are significantly affected by such parameters as heat input during welding, the composition of steel metal used, and the in-process cooling and heating of the welded zone [7]. In-process laser heating was introduced in [8] where a laser beam was used as a preheating source during friction stir welding. Preheating in this process aids in softening the metal before stirring and thus increasing the speed of the rotating tool and less work is now required by the tool to raise the temperature of the workpiece. Using this technique the heat generated by the tool is reduced and the tool life is increased. Moreover, the higher rotational speeds and the higher cooling rates attained (above 600 mm/min) by laser-assisted FSW prevented the formation of brittle martensite which increases the hardness of the welded zone [9]. For more sustainable laser-assisted friction stir welding processes, the process will have to capture some of the elements defined in [10] to characterize sustainability: (1) power consumption, (2) operational safety, (3) personnel health, (4) environmental impact, (5) manufacturing costs and (6) waste management.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

Although laser assisted FSW requires higher power inputs but with preheating higher production rates can be achieved thus decreasing the total production costs. Moreover, it is believed that achieving a better quality product especially through enhancing surface integrity is a main aspect of manufacturing sustainability. Using preheating in FSW through laser beam was found [11] to enhance surface integrity through increasing the surface hardness via refined microstructure evolution. In addition to that the approach followed which is numerical simulation for optimization purposes is proven to decrease costs relative to experimental approaches. In this paper, a finite element model was developed to simulate the Laser-assisted FSW and optimize the process parameters to enhance surface integrity and microstructural properties which affect the tool ware resistance and as a result the sustainability of the process. The commercial modelling software DEFORM-3D™ (Scientific Forming Technologies Corporation, 2545 Farmers Drive, Suite 200, Columbus, Ohio 43235) was used as a fully thermo-mechanically coupled FE model to simulate the process. The model accounted for phase transformation taking place and was validated against experimental data.

2 THE FEM MODEL

2.1 Parts and Meshes

A thermo-mechanically coupled model using the FE software DEFORM was implemented to model the friction stir welding of carbon steel. As shown in figure 1, the model comprises the tool, the workpiece, and the backing plate. Also shown superimposed on the meshed geometry is a rendering of the in-process laser source. To model the laser source, a heat source circular window with constant heat flux was defined. The circular window is of diameter 2 mm and is placed 5 mm in front of the tool. The power of the laser was 2kW.

Both the tool and the backing plate were modeled as rigid un-deformable bodies where only heat transfer was accounted. On the other hand the workpiece was modeled as a plastic body subject to deformation and heat. The two plates to be welded were modeled as one block to avoid numerical instabilities at the contact.

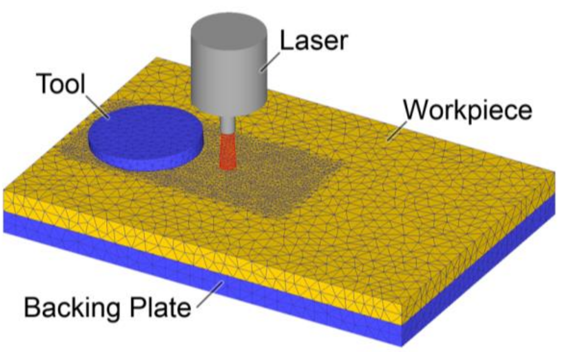


Figure 1: The meshed FE model showing the tool, workpiece, and backing plate (under the workpiece). Shown superimposed is a rendering of the in-process laser source.

The considered tool was a cylindrical shoulder 15mm in diameter. From the bottom of the shoulder, a 6 mm diameter smooth unthreaded pin extrudes 3.2 mm. The tool was tilted 3° about the vertical axis in the processing direction to further improve material flow. Both the workpiece and the backing plate had an area of 60x40 mm2 and a thickness of 3.2 mm.

Tetrahedral elements were used in the FEM model. The tool and the backing plate were meshed for thermal analysis purposes only with each containing around 10000 and 5000 elements respectively while the workpiece had around 24000 elements. To further capture the state variables at the tool-workpiece interface, a rectangular mesh control window was applied around the processing area of interest where finer mesh elements (around 0.3 mm) were created as shown in Figure 6.

2.2 Material Modeling

The material used for the tool and the backing plate was WC based alloy. As for the workpiece, it is believed that the final weld mechanical properties are strictly dependent on the volume fraction of phases present. Therefore, AISI 1045 (workpiece material) was defined as a mixture of phases. Specifically three phases were defined: martensite, austenite, and pearlite. The transformation to any of the phases was defined according phase transformation, isothermal, and continuous cooling transformation diagrams. The functions recommended by DEFORM are listed below in Table 1 and which were used along with the appropriate generated latent heat values. The initial volume fraction of the elements was defined as 100 percent pearlite which is predominatly the case of as received mild-carbon steels. Each phase has its own materiel properties which are, in turn, function of temperature. Similarly, each of the phases has its own flow stress equation. The linear hardening equation used to formulate the stress equation was

$$\bar{\sigma} = Y(T, A) + H(T, A)\bar{\varepsilon} \qquad (1)$$

where,

A = Atom content

T = Temperature

$\bar{\varepsilon}$ = Effective plastic strain

$\bar{\sigma}$ = Flow stress

Y = Initial yield stress (temperature dependent)

H = Strain hardening (temperature dependent)

Table 1: Phase Transformation Models

Phase 1	Phase 2	Transformation Model
Austenite	Martensite	Magee's Equation
Austenite	Pearlite	Diffusion(TTT curve)
Martensite	Austenite	Diffusion(Simplified)
Pearlite	Austenite	Diffusion(Simplified)

2.3 Friction Modeling

Friction at the tool-workpiece interface is a very complex process due to the variation of temperature, strain rate, and stress which make friction modeling a difficult task. In [12] a numerical model with experimental evidence was developed to estimate the shear friction coefficient in FSW. The model uses the tool speed and dimensions to estimate the shear friction coefficient as shown below:

$$\mu_f = \mu_0 \exp(-\lambda \delta \omega r) \qquad (2)$$

where δ is the percentage sticking and r is the radial distance from the tool axis for the point in consideration. The values used were as follows: μ_0= 0.4, δ= 0.4, ω=62.8 radians, r= 0.003m and constant λ was 1s/m [12].

2.4 Boundary Conditions

Heat transfer with the environment was accounted for the three meshed objects (tool, workpiece, and backing plate) via a convective heat coefficient of 20 W/(m2 ºC) at a constant temperature set at 293K for the surrounding environment. The heat transfer coefficient between the tool-workpiece and the backing plate-workpiece interfaces was set to 11 kW/(m2ºC). Local re-meshing was triggered by a relative interference ratio of 70% between contacting edges. This would ensure the integrity of the workpiece geometry during deformation. The simulation time step selection should be optimized to prevent redundant calculations while preserving the state variables' accuracy. The time step in the simulation was determined based on the tool rotational speed and the minimum element size to guarantee a calculation step every 5 degrees of the tool rotation. Simulation time was further reduced by neglecting the plunging phase of FSW and taking into consideration the traversing phase alone. The tool final plunged shape was cut from the workpiece geometric model to account for the deformation produced by the plunging phase. A dwelling phase was added at the beginning of each run where the tool spins in its place to raise the temperature at the stir zone to the plunging elevated levels. In tool movement definition, a trapezoidal speed profile with a rise time of 0.5s was used. This would ensure a smooth processing start and prevent voids during the plunging stage.

3 MODEL VALIDATION

The FEM model was validated against experimental data available in the literature by tracking the temperature history of an observation point at the seam line at a distance of 0.5 mm above the shoulder for two different test cases. The processing parameters of both cases are described in table 2.

Table 2: Processing parameters of the validation test cases

Property	Case 1	Case 2
Rotational speed (RPM)	600	600
Traverse speed (mm/min)	100	400

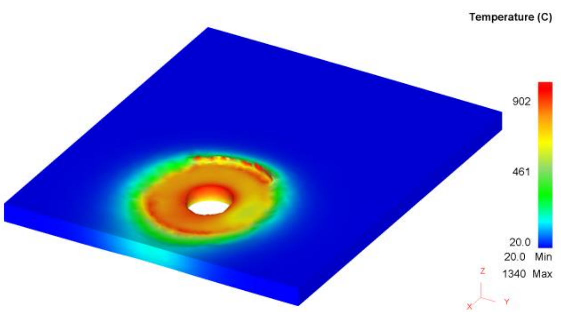


Figure 2: Temperature contour plot in workpiece for case 2 (rotational spindle speed = 600 rpm, traverse speed = 400 mm/min) after 6 seconds of welding

Figure 2 shows the temperature contours for case 2 (rotational spindle speed = 600 rpm, traverse speed = 400 mm/min) where peak temperature is located at the pin/tool interface as one would normally expect in an FSW process.

Plotted in Figure 3 are the simulated temperature profiles versus time for 2 cases: normal FSW and laser-assisted FSW. Co-plotted are the peak temperatures measured in [8]. It can be seen from the Figure that the peak simulated temperature is very close to the experimentally measured maximum temperature for case 2 for both cases: normal FSW and in-process laser assisted FSW.

Another comparison is made in Figure 4 where the peak temperatures for rotational spindle speed = 600 rpm are plotted against traverse speed at 100 and 400 mm/min. Although the peak temperatures are not exactly matching between experimental and numerical aproaches, the differences in both cases are less than 16% and a similar trend of decreasing temperature with increasing advancing speed is reached. Figures 3 and 4 constitute the model validation phase in this work.

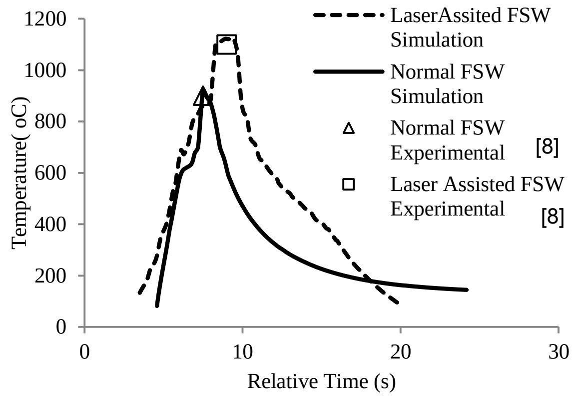


Figure 3: Simulation temperature profile with experimental [8] peak temperature for case 2 (rotational spindle speed = 600 rpm).

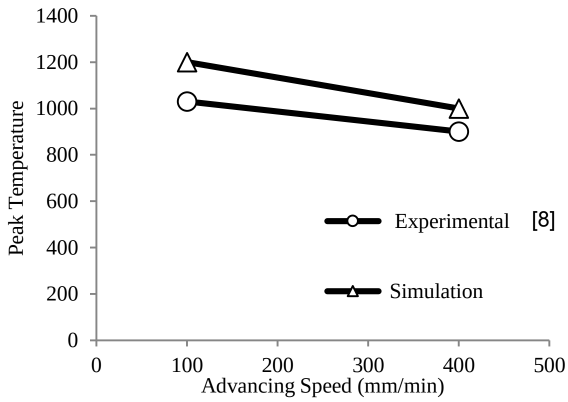


Figure 4: Peak temperatures versus advancing speed for experimental [8] and simulation test cases (rotational spindle speed = 600 rpm).

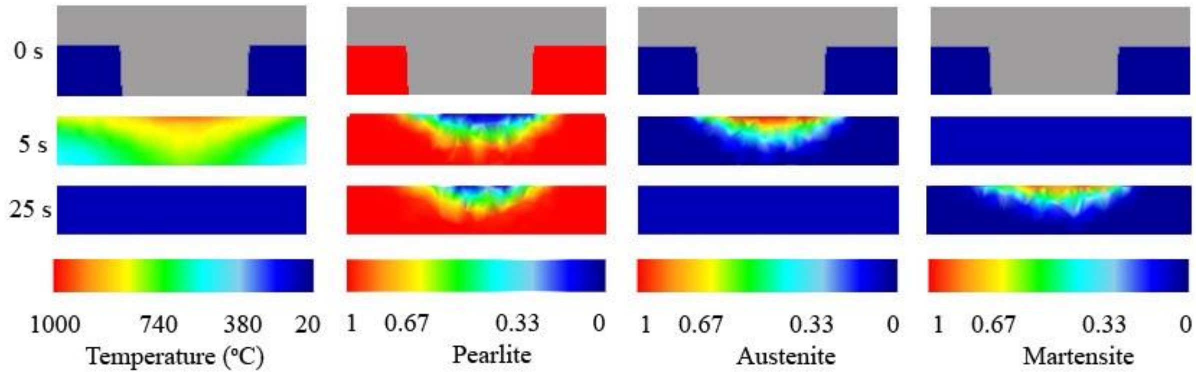


Figure 5: Phase transformation with time as the tool moves away for the normal friction stir welding (RPM=600; V=400 mm/min)

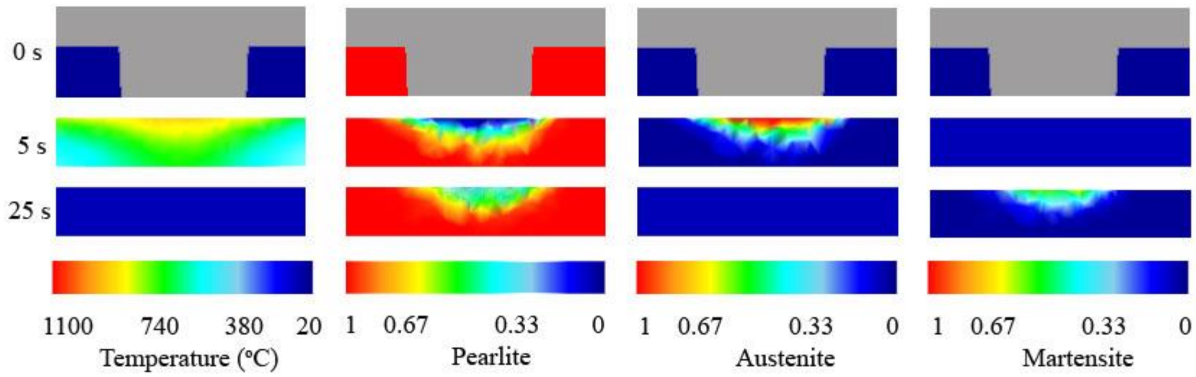


Figure 6: Phase transformation with time as tool moves away for laser assisted friction stir welding (RPM=600; V=400 mm/min)

4 RESULTS

4.1 Phase transformations

The resulting mechanical properties of carbon steel joints ultimately depend on the intermetallic phases present and, thus, on the heating and cooling histories during the process. During FSW of carbon steels, temperature exceeds the transition temperature (about 727 ºC for many steels) at which austenite begins to form upon heating. Therefore, transformations form austenite to other forms such as pearlite, martensite, and bainite will take place afterwards. Furthermore, the amount and type of these transformations is directly affected by the maximum temperature (mostly related to rotational speed) and cooling rate (mostly related to advancing speed). Other external heating (e.g., laser) and cooling (cryogenic) sources during FSW/FSP also play a critical role in altering these phase transformations and the resulting grain size for many materials [13,14].

In this work, modeling of phase transformations was made possible in DEFORM by defining a material subject to steel phase transformations according to the scenarios listed in Table 1. To illustrate, a section at the pin center was considered and the history of temperature with corresponding phases as the pin moves away was monitored (Figure 5, left). From Figure 5, it is clear that after exceeding 727ºC pearlite starts to transform into austenite specifically at the stir zone. Then, after reaching the maximum temperature at about 5 seconds, the cooling stage starts. In the cooling stage, some of the austenite transforms to martensite and some transform back to pearlite. This formation of martensite was reported using a transmission electron microscope, TEM, by [8] while using the same processing parameters. It is also worth mentioning that from Figures 5 and 6 one can notice that larger phase transformations take place at the advancing side as compared with the receding side. This may be expected given that larger deformations take place at that side compared with the receding side and, thus, resulting in higher temperatures (heating and cooling).

4.2 Effect of In-process Laser Heating

The application of laser increases the maximum temperature during FSW as shown in Figure 6 by about 100ºC compared to normal FSW. This increase in temperature slowed the cooling rate which is believed to be behind martensite formation. The formation of brittle martensite in FSW joints is usually avoided. Therefore, in order to enhance the weld hardness, and thus weld sustainability, some may add pre-heating sources to lower the cooling rate thus reducing martensite formation. Laser-assisted heating was found to be a suitable method used to aid in the heating the joint during FSW steel joining [8]. Moreover, with laser-assisted FSW, higher weld speeds can be achieved increasing the productivity and, thus, process and product sustainability. Contrasting Figure 5 with Figure 6, one can notice that less pearlite is transformed to marternsite during in laser-assisted FSW. This is expected because of the lower cooling rate with the application of laser and also because more time is spent while cooling from higher peak temperatures.

5 SUMMARY AND CONCLUSIONS

An FEM model was developed to simulate the in-process laser assisted friction stir welding of AISI 1045 carbon steel.

The simulation results of peak temperatures of the weld were validated against experimental work reported by other researchers [8]. The effect of advancing speed on weld temperature was examined where peak temperatures were found to decrease with increasing traverse welding speed. With laser assistance, however, higher welding temperatures can now be reached faster at higher welding speeds thus increasing the sustainability of the process. Furthermore, the resulting phase transformations, which have direct effect on the microstructure and, thus, the mechanical properties of the weld were successfully accounted in the model. It was found that with laser-assisted processing, smaller phase fraction of the brittle martensite phase is formed at the stir zone resulting in enhanced properties of the welded joint and, thus, enhancing weld sustainability. It is believed that such model can be used for optimization purposes leading to more sustainable processes and, more importantly, sustainable products.

6 ACKNOWLEDGMENTS

This publication was made possible by the National Priorities Research Program (NPRP) grant # 09-611-2-236 from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors. The second author gratefully acknowledges the support of Consolidated Contractors Company (CCC) through the CCC Doctoral Fellowship in Manufacturing.

7 REFERENCES

[1]. K.V. Jata and S.L. Semiatin. 2000. Continues dynamic recrystallization during friction stir welding of high strength aluminum alloys. *Scripta mater* 43 (2000) 743-749.

[2]. M. Guerra, C. Schmidt, J.C. McClure, L.E. Murr, A.C. Nunes, 2002. Flow patterns during friction stir welding. *Materials Characterization* 49 (2003) 95–101.

[3]. L. Cui, H. Fujii, N. Tsuji, K. Nogi.2007. Friction stir welding of a high carbon steel. *Scripta Materialia* 56 (2007) 637–640.

[4]. R. Mishra, Z. Ma. 2005. Friction stir welding and processing. Materials *Science and Engineering* R 50 (2005) 1–78.

[5]. A. Ozekcin, H. Jin, J. Koo, N. Bangaru, R. Ayer. 2004. A Microstructural Study of Friction Stir Welded Joints of Carbon Steels. *International Journal of Offshore and Polar Engineering*.

[6]. J Cho, Donald E. Boyce, P. Dawson. 2005. Modeling strain hardening and texture evolution in friction stir welding of stainless steel. *Materials Science and Engineering* A 398 (2005) 146–163.

[7]. H. Fujii, L. Cui, N. Tsuji, M. Maeda, K. Nakata, K. Nogi.2006. Friction stir welding of carbon steels. *Materials Science and Engineering* A 429 (2006) 50–57.

[8]. Y. Sun, Y. Konishi, M. Kamai, H. Fujii. Microstructure and mechanical properties of S45C steel prepared by laser-assisted friction stir welding. *Materials and Design* 47 (2013) 842–849. Ueji R, Fujii H, Cui L, Nishioka A, Kunishige K, Nogi K. Friction stir welding of ultrafine grained plain low-carbon steel formed by the Martensite process. Mater Sci Eng A 2006;423(1–2):324–30

[9]. Jawahir, I.S. and Dillon, O.J., 2007, Sustainable Manufacturing Processes: New Challenges for Developing Predictive Models and Optimization Techniques, (Keynote Paper), Proc. 1st International Conference on Sustainable Manufacturing (SM1), Montreal, Canada, October 18-19, 2007, pp. 1-19.

[10]. Jawahir, I.S, Brinksmeier, E., M'Saoubi, R., Aspinwall, D.K., Outerio, J.C., Meyer, D., Umbrello, D., Jayal, A.D., 2011, Surface Integrity in material removal process: Recent Advances, CIRP Annals – Manufacturing Technology, 60:603-626.

[11]. Buffa, G., Fratini, L., and Shivpuri, R., 2007, "CDRX Modelling in Friction Stir Welding of AA7075-T6 Aluminum Alloy: Analytical Approaches," Journal of Materials Processing Technology, 191(1-3) pp. 356-359.

[12]. Nandan, R., Prabu, B., De, A., & Debroy, T., 2007, Improving reliability of heat transfer and materials flow calculations during friction stir welding of dissimilar aluminum alloys. WELDING JOURNAL-NEWYORK-, 86(10), 313.

[13]. A.H. Kheireddine, A. H. Ammouri, R. F. Hamade, G. T. Kridli, 2012, FEM analysis of the effects of cooling techniques on the microstructure of aluminum 7075 friction stir welded joints, IMECE2012-88943, proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition, IMECE2012, November 9-15, 2012, Houston, Texas, USA

[14]. A. H. Ammouri, A. H. Kheireddine, R. F. Hamade, G. T. Kridli, 2013, FEM optimization of process parameters and in-process cooling in the friction stir processing of magnesium alloy az31b, IMECE2013-62468, ASME 2013 International Mechanical Engineering Congress & Exposition, IMECE2013, Nov 15-21, 2013, San Diego, USA.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

8.3 Cutting tool manufacturing: a sustainability perspective

Giovanni Loglisci [1], Paolo Claudio Priarone [1], Luca Settineri [1]

[1] Politecnico di Torino, Department of Management and Production Engineering,
Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract

Over the last few years, sustainability has become a major challenge for manufacturing systems, due to the rising awareness of energy consumption and to the associated environmental impact of processes. In order to measure the sustainability of a specific process, metrics for sustainable manufacturing were developed and proposed in the scientific literature. The research activities presented in this paper aim to apply a structured sustainable approach to a tool manufacturing process. More in detail, the production of a tap, starting from the raw material up to the finished product, is investigated. The process, divided into the various stages of the manufacturing route, is evaluated from a technological and sustainable point of view. Results provides a basis for decision-making, and are expected to be incorporated into the business strategy development processes.

Keywords:
Machining, Process consumption, Sustainable manufacturing, Tap production

1 INTRODUCTION

The rising awareness of the manufacturing impact on the environment, on the energy, and on resources consumption drives companies to the evaluation of their operations, considering also their sustainability. It has been widely agreed that sustainable manufacturing is a key component of sustainable development, balancing three principal requirements related to environmental, economic, and social objectives [1]. According to the National Council for Advanced Manufacturing (NACFAM, USA), sustainable manufacturing is defined as “the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers” [2].

Focusing on the processes, there is still the need to achieve optimized technological improvement and process planning for reducing energy and resource consumption, toxic wastes, occupational hazards, etc. (Figure 1), and for improving product life by manipulating process-induced surface quality/integrity.

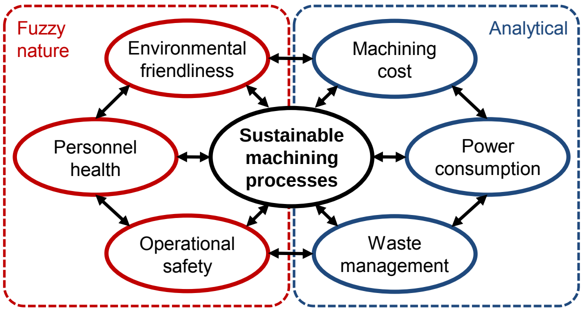


Figure 1. Basic sustainability elements in machining [3].

Industry is responsible for a significant percentage (around 25% in 2010 [4]) of the final energy consumption in Europe. Metrics for sustainable manufacturing were developed to quantify the performances of a specific process: for instance, the OECD toolkit provides a suitable set of indicators for analysis at different levels, from process and product to overall facility [5].

In order to achieve sustainability goals it is necessary to understand how the different variables influence the machining process [6], and many studies have been conducted in order to monitor and to improve the energy efficiency and to reduce the resources consumption. Mori et al. [7] investigated concrete ways to reduce power consumption, focusing on servo and spindle motors, which have the highest energy demands in machine tools. Drossel et al. [8] proposed HSC and HPC for improving resource and energy efficiency. Gontarz et al. [9] measured the energy consumption of an entire plant (manufacturing systems and machine tools) suggesting a case by case approach. Behrendt et al. [10] presented a three step methodology calculating the energy consumption of small, medium and large machine tools, considering the idle mode, the run-time mode and the production mode.

Power consumption is directly related to the CO_2 emissions (Figure 2), as a function of the national electricity mix (Figure 3), but it is not the only issue manufacturers have great interest in. Broader researches have been conducted analyzing the manufacturing route that brings towards the product. Li et al. [11] studied a grinding case and proposed an integrated approach to evaluate the eco-efficiency of such manufacturing process. Linke and Overcash [12] also focused on a grinding case, as it is one of the most-energy intensive operations among all machining processes. They monitored inputs (non product material, product material, energy, worker, grinding machine tool) and the outputs

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

(product, waste), providing a wide overview of the process up to the product. Klocke et al. [13] presented two different case studies within the manufacturing of metal parts, and analyzed the main perpetrators of the ecological impact regarding different consumption types in the industrial environment. Zhang et al. [14] investigated the manufacturing of metallic components for the automotive sector evaluating the total life cycle aiming at the sustainable improvement.

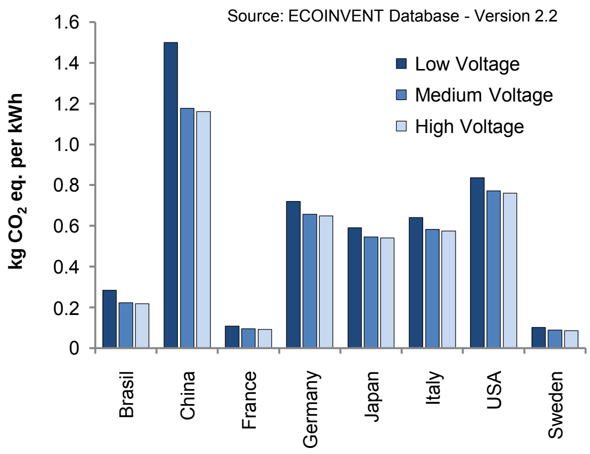


Figure 2. CO_2 emissions for the production of 1 kWh [15].

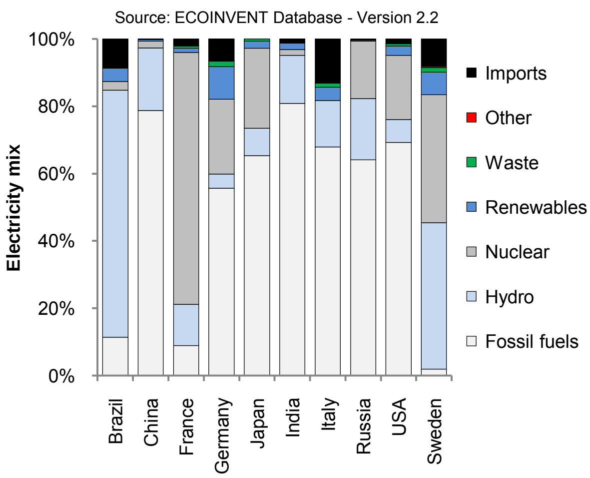


Figure 3. Electricity mix for different countries [15].

In this context, the present research work describes a structured sustainable approach to a complete tool manufacturing process. In the following, the framework is detailed with the description of all the subsequent operations, the analytic proposed approach is presented, and the correlation between each manufacturing stage and the different contributes on process consumption are critically analyzed.

2 TAP MANUFACTURING PROCESS

The production process for uncoated M10 spiral point taps, cutting tools designed for the execution of threaded through holes, was analysed in this research. Figure 4 details the different stages of the manufacturing route, on the basis of the conventional production procedures of the company UFS S.r.l. (Sparone, Italy), specialized in the manufacture of cutting tools. The taps are made from a W-alloyed high speed steel (HSS), produced by powder metallurgy and subjected to a cold drawing post-processing operation. The material is supplied in the form of round bars, with an expected hardness of 320 HB maximum. The bars were of 10.5 mm diameter and 3200 mm length.

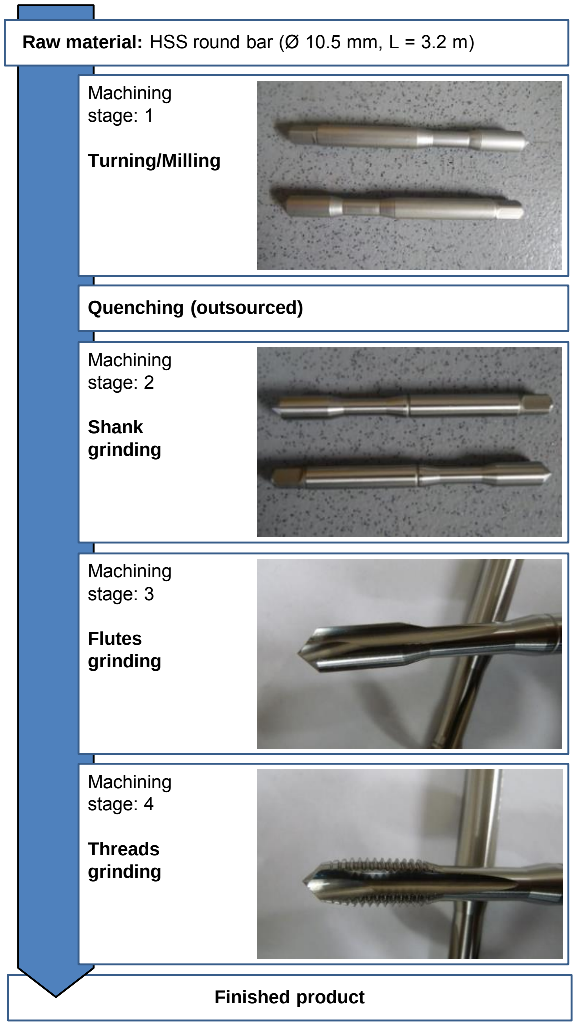


Figure 4. Spiral point tap production process.

The first machining stage is performed by a CITIZEN L20 sliding-head CNC lathe, fitted out with an automatic bar-loading apparatus. As it can be deduced from Figure 4, subsequent cutting operations (as centre-holes execution, longitudinal external turning, milling of the square cross-section at one end of the tool, parting of the semi-finished component) are carried out. Afterwards, the tap is subjected to a quenching heat-treatment. This activity is outsourced, therefore it was not considered at this level of the study. Then, the tool shank is grinded (second manufacturing stage), in order to accomplish the desired tolerance values, by means of a ZEMA cylindrical CNC grinding machine. After that, the three tool flutes were obtained (third stage) using a WALTER grinder retro-fitted by TAMIC (model TGG-SH-20-IC), and specifically designed to machine these geometries. Finally, on a GBA CNC grinding machine, the threads were manufactured (fourth stage). Tools and cutting conditions applied in each phase of the manufacturing route were chosen according to the standard process parameters adopted by the company for the production of HSS M10 spiral point taps. Figure 5 reports the cycle time for each stage: these values add up the cutting time and the time for the automatic workpiece handling inside the machine tools, whilst the time required for moving the semi-finished pieces between two successive workstations is not considered.

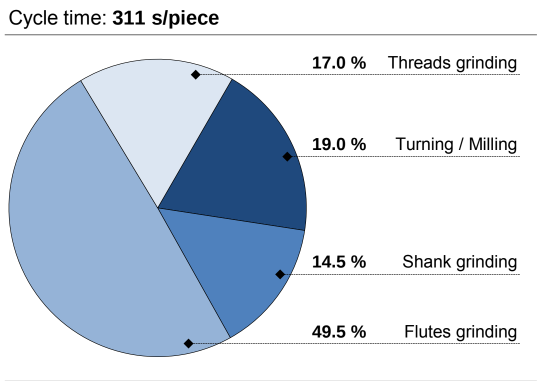


Figure 5. Cycle time for the production of a spiral point tap.

3 APPROACH TO PROCESS ANALYSIS

In order to analyze the whole tap production process, for each *i*-th manufacturing stage the different machine tools, together with their auxiliary apparatus, were assumed as black-boxes. As shown in Figure 6, during the processing from the workpiece to the (semi-)finished component, the major resources consumed during machining operations include electricity, lubricants, water, cutting tools and material [16].

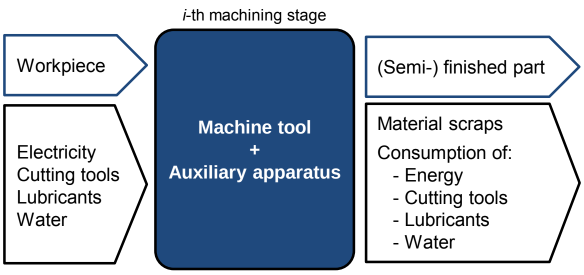


Figure 6. Experimental approach to process analysis.

The absorbed power was measured by a Chauvin Arnoux PEL 103 power/energy data logger, which was clamped onto the electricity supply wires of the machine tools. For each process step, the energy consumption was acquired during the steady-state manufacturing of 200 taps, and it was afterwards partitioned for each produced part. At this level of analysis, the power demand of machine tools was not split into the three different contributions (idle mode, run-time mode and production mode) proposed by Damhus and Gutowsky [17], but it was entirely considered. Only for the cases of flutes and threads grinding, the contributions of filtering/cooling external equipments were separately analyzed, since they are stand-alone units that significantly affect the total energy consumption.

The lubrication of each process was carried out using mineral cutting oils. More in detail, an oil supplied by Shell was applied for turning/milling, shank and flutes grinding processes, whilst an oil provided by Castrol was employed for threads grinding operations. For all the phases, not being used emulsions, the waste of water for lubrication is zero. In general terms, the cutting fluid used for lubrication is assumed to diverge into four paths during the machining process: (1) vapour waste stream generated through cutting fluid diffusion into the surrounding environment, (2) liquid waste steam created through fluid coating on the chips generated during the machining process, (3) liquid waste steam resulting from cutting fluid coating of the workpiece, and (4) lubricant flow collected and re-circulated through the system [18]. An accurate evaluation of the oil consumption for a small/medium production batch is relatively a problematic issue, being the direct measures subjected to uncertainties and errors. In order to quantify the amount of lubricant consumed for a single unit production and for each *i*-th manufacturing stage, the annual oil consumption was divided by the number of taps produced in one year, for every *j*-th machine tool (Equation 1). The amount of oil that was refilled and the complete oil changes were both taken into account. It is worth pointing that, in Equation 1, the *i*-th stage equates the *j*-th machine tool. This indirect measure was assumed to be acceptable for a first-attempt evaluation, since such machine tools are specifically dedicated to the production of taps fairly homogeneous in geometry and size (i.e. within the range from M8 to M12), although belonging to different production series/batches.

$$Oil\ consumption\ _{1\,tap}^{i-th\ stage} = \frac{Total\ oil\ consumption\ _{1\,year}^{j-th\ machine\,tool}}{Number\ of\ taps\ machined\ _{1\,year}^{j-th\ machine\,tool}} \quad (1)$$

Each manufacturing step involves different cutting tools. For the first stage, centre drills, parting blades, inserts for external turning, and cutters for the insert mill are used. Moreover, four different grinding wheels are employed for shank, flutes, spiral point, and threads machining. For each case, the tool consumption was allocated to the single produced unit according to Equation 2, in which the denominator is the overall number of taps produced before the replacement of the *k*-th cutting tool.

$$Tool\ consumption\ _{1\,tap}^{k-th\ cutting tool} = \frac{1^{\ k-th\ cutting\ tool}}{Number\ of\ taps\ machined\ ^{k-th\ cutting\ tool}} \quad (2)$$

Finally, the loss of workpiece material due to the chip removal was directly obtained by the CAD/CAM software installed in the control units of the machine tools. In addition, the HSS bar scrap was weighted and subdivided by the number of taps produced by the bar itself.

4 RESULTS AND DISCUSSION

4.1 Power consumption

Figure 7 reports the measured energy consumption results. Overall, the production of a spiral point tap demands 1.64 kWh of electric energy. The major consumption is related to the flutes grinding, which also involves almost 50% of cycle time (Figure 5), while the turning/milling operations are basically negligible, although removing the highest percentage of workpiece material (60.4%), as shown hereafter in Figure 8. Shank and threads grinding absorbed 15.7% and 21.0% of measured energy, respectively.

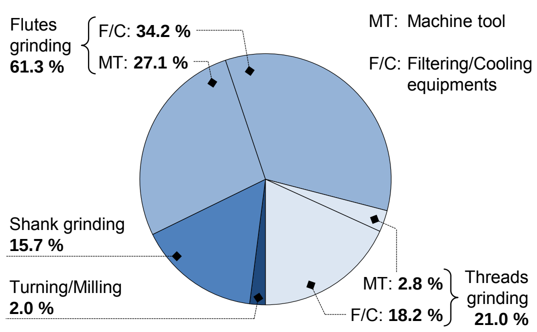


Figure 7. Measured energy consumption.

Flutes and threads grinding account together for approximately four fifths of the total consumption, and it is useful to remark that a considerable energy fraction goes to the filtering/cooling equipments. This result is particularly evident for the threads grinding operations, in which the consumption of the stand-alone machine tool is very low if compared to that of the external unit. These apparatus are needed to separate the lubricant (oil) from the chips by means of a centrifugal machine, which always rotates at a constant speed when the machine tool is turned on. Moreover, they have a cooling system for avoiding lubricant overheating, that is activated at regular time cycles when the measured oil temperature reaches a threshold value. In addition, each unit is equipped with pumps that allow the fluid re-circulation.

4.2 Workpiece material loss

As far as the workpiece material loss is analyzed, Figure 8 highlights all the contributions. The percentage values due to machining operations (turning, milling, and grinding) are obviously related to the different geometries obtained on the tap in each phase, being the turning/milling and the threads grinding the more and the less wasteful processes, respectively.

Furthermore, each bar can not be processed for all the 3200 mm length, and this can be traced back to two main reasons. Firstly, a minimum bar length is needed to ensure a rigid clamping in the chuck of the CNC lathe. Secondly, the length of a bar is not an exact multiple of the length of a tool. As a results, the bar scrap was also shared for every produced tap: the experimentally measured value of 0.17 kg (on average) per each bar was divided by the number of the tools realized with the bar itself, and this value resulted to be the 15.8% of the total material loss.

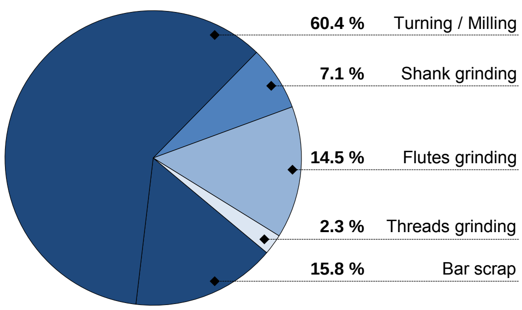


Figure 8. Workpiece material loss.

4.3 Oil consumption

The oil consumption (Figure 9) closely follows the electrical energy consumption trend, with comparable ratios between the different manufacturing stages. The estimated oil waste is quite low for the production of a single tap, but the discussion should be extended with a view on the several thousand units produced per year.

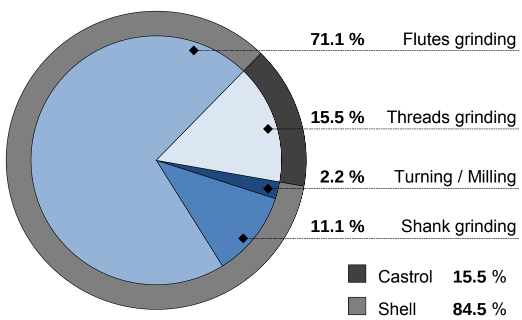


Figure 9. Estimated oil consumption.

The Shell's oil represents the 84.5% of total oil consumption, therefore its sustainability performances should be particularly taken into account. As for others highly refined mineral oils, and according to the EC classification, this oil does not present any specific risk for human health, even if prolonged or repeated exposure may cause dermatitis. Also, it is not classified as dangerous for the environment, even if it is not expected to be readily biodegradable.

4.4 Tool consumption

The spiral point tap is a cutting tool manufactured by other cutting tools. Worn tools have to be periodically substituted when the tool wear is too high to reach satisfactory surfaces quality and to guarantee strict tolerances. The values above each histogram bar in Figure 10 report the percentage of tool consumption. A value of 0.5 %/piece means that the *k*-th tool was consumed of 0.5% for the production of one tap, or else that 200 taps are produced prior to the worn tool substitution. From the graph observation it is evident that the turning/ milling operations should be considered and deeply analyzed for process optimization.

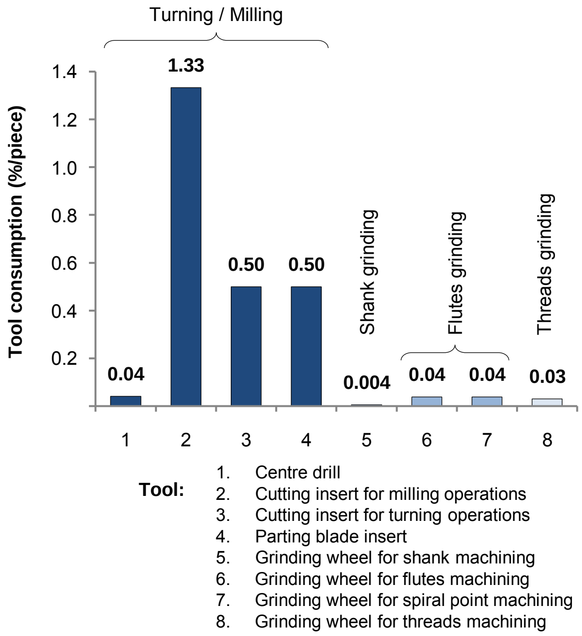


Figure 10. Estimated tool consumption.

5 CONCLUSIONS AND OUTLOOKS

In this paper, an analytical approach to cutting tool production has been implemented, aiming to reach an increased consciousness for sustainable manufacturing. The presented methodology does not focus only on absorbed electric energy, which represents a significant parameter, but it estimates also every consumption source. Moreover, this approach can be easily implemented at a company level, as the required data are not difficult to collect and are mostly known by the production department.

The results highlight the process stages which can be optimized, even if some technological constraints cannot be overcome. For instance, the chips produced by all the cutting operations resulted in a 44.5% reduction of the weight of the raw bar portion needed to manufacture a single tap. This value can be hardly reduced during the manufacturing route, unless changing the tap geometry (at the project stage) or the workpiece geometry (if economically possible). In this context, the analysis could be extended to the comparison between the use of near-net-shape WC sintered parts instead of WC bars.

Overall, it has been shown that the flutes grinding consumes most of the resources in terms of electric energy and lubricants. A way forward to enhance this stage could be the reduction of the time cycle, by modifying the process parameters (without adversely affecting the quality/integrity of the finished product), or by optimizing the sequence of machining operations (as the tool path strategy, the workpiece positioning, etc.).

Another issue that has to be investigated is the choice of the type of lubricant. Being identified the most commonly used oil, alternative and more sustainable solutions should be evaluated, aiming to zero (or, at least, reduced) toxicity and pollution levels. Finally, efforts to increase tool lifetime in turning and milling operations should be undertaken. All these tasks requires careful and in-depth analyses of the trade-off between technological and sustainable needs.

6 ACKNOWLEDGEMENTS

The authors kindly acknowledge Mr. Roberto Balaso, of UFS S.r.l. (Sparone), for his support in process analysis.

7 REFERENCES

[1] Krajnc, D., Glavič, P., 2003, Indicators of sustainable production, Clean Technologies and Environmental Policy 5, 279-288.

[2] National Council for Advanced Manufacturing, 2009, Sustainable Manufacturing, http://www.nacfam.org/ (Accessed on Oct. 7th, 2012).

[3] Jayal, A.D., Badurdeen, F., Dillon, O.W. Jr., Jawahir, I.S., 2010, Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels, CIRP Journal of Manufacturing Science and Technology 2, 144-152.

[4] European Commission - Eurostat, 2010, Energy consumption by sectors (tsdpc320), Luxembourg.

[5] Bordt, M., 2009, OECD Sustainable Manufacturing Toolkit, Sustainability and U.S. Competitiveness Summit, U.S. Dept. of Commerce, Oct. 8th, 2009.

[6] Rotella, G., Lu, T., Settineri, L., Jawahir, I.S., 2012, Machining of AA 7075 aluminum alloy: A process optimization for sustainability, In: Proceedings of 10th Global Conference on Sustainable Manufacturing, Istanbul, 501-506.

[7] Mori, M., Fujishima, M., Inamasu, Y., Oda, Y., 2011, A study on energy efficiency improvement for machine tools, CIRP Annals - Manufacturing Technology 60, 145-148.

[8] Drossel, W., Neugebauer, R.; Wertheim, R., 2012, High speed cutting and high-performance cutting for improving resource and energy efficiency, In: Proceedings of 10th Global Conference on Sustainable Manufacturing, Istanbul, 211-218.

[9] Gontarz, A., Plehn, J., Sproedt, A., Weiss,L., Wegener, K., 2012, Resource consumption measurement in manufacturing environments, In: Proceedings of 10th Global Conference on Sustainable Manufacturing, Istanbul, 557-562.

[10] Behrendt, T., Zein, A., Min, S., 2012, Development of an energy consumption monitoring procedures for machine tools, CIRP Annals-Manufacturing Technology 61, 43-46.

[11] Li, W., Winter, M., Kara, S., Herrmann, C., 2012, Eco-efficiency of manufacturing processes: A grinding case, CIRP Annals - Manufacturing Technology 61, 59-62.

[12] Linke, B., Overcash, M., 2012, Life cycle analysis of grinding, In: Leveraging technology for a sustainable world, Springer, 293-298.

[13] Klocke, F., Döbbeler, B., Binder, M., Schlosser, R., Lung, D., 2012, Ecological evaluation of main origins of consumption in manufacturing within the automotive sector, In: Proceedings of 10th Global Conference on Sustainable Manufacturing, Istanbul, 231-236.

[14] Zhang, X., Shuaib, M., Huang, A., Badurdeen, F., Rouch, K., Jawahir, I.S., 2012, Total life cycle based product sustainability improvement: End-of-life strategy analysis for metallic automotive components, In: Proceedings of 10th Global Conference on Sustainable Manufacturing, Istanbul, 507-512.

[15] ECOINVENT Database V.2.2, 2010, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

[16] Diaz, N., Dornfeld, D., 2012, Cost and energy consumption optimization product manufacture in flexible manufacturing system, In: Leveraging technology for a sustainable world, Springer, 411-416.

[17] Dahmus, J.B., Gutowsky, T.G., 2004, An environmental analysis of machining. In: Proceedings of IMECE 2004 ASME International Mechanical Engineering Congress and RD&D Expo, Paper IMECE2004-62600.

[18] Munoz, A., Sheng, P., 1995, Analytical approach for determining the environmental impact of machining processes, Journal of Materials Processing Technology 53, 736-758.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

8.4 Sustainability of energy and material consumption within manufacturing processes

R. Schlosser
Premium Aerotec GmbH, Varel, Germany

Abstract
A model for the evaluation of machining processes with all direct in- and outgoing energy and material flows as well as the plant infrastructure installations is presented within this paper. The flows were captured, connected to functional units and evaluated in combination with a life cycle inventory data base regarding typical ecological indicators.
Former studies identified that the peripheries of manufacturing processes are responsible for the major part of the energy and resource consumption and that the process effectiveness is only dependent on the used machine tool and peripheral components. Within this paper it will be shown, that this assumption is not totally correct and that the generated efficiency values for the different processes are influenced in huge amount by process parameter variation.
Keywords:
Machining Processes, Sustainability, Life Cycle Assessment

1 INTRODUCTION

Since climate protection and reduction of carbon emissions have gained increasing significance in research, industry and legislation, it is not only important to reduce energy consumption and emissions of products during the use phase, but throughout the whole life cycle [1][2][3].

The Life Cycle Assessment (LCA) corresponding to DIN EN ISO 14040 and 14044 is a suitable method for the assessment of products [4][5]. So far the manufacturing phase of products is often neglected or only simplified respected within these LCA studies [6][7].

2 APPROACH

Besides the environmental also the social impact as well as the costs have to be respected to evaluate the sustainability of products or processes.

As changes for improvement of one product life cycle phase or production step might also effect the energy and resource consumption in another phase either positively or negatively it is essential to evaluate all changes done in one life cycle phase across the whole life cycle to guarantee an overall optimisation [8]. The most important life cycle phase during which product features still can be influenced is the manufacturing phase [9].

Due to both reasons above the evaluation of the sustainability of products is a very complex process which requires computational support. So far several software tools were developed to support LCAs (GaBi, Umberto, SimaPro etc.). These software tools use own or open source databases with life cycle inventory data of different material and energy flows. So far manufacturing processes are not available within these software tools or are aggregated together with the work piece material.

Therefore the aim of this paper is to setup a parameterised model of machining processes within the manufacturing phase. The GaBi V5 Software of PE International is chosen for the implementation as this software tool is prepared for the evaluation of all three dimensions of sustainability by LCA, Life Cycle Costing (LCC) as well as a social Life Cycle Assessment (SLCA).

Although the possibility of a SLCA is prepared within the GaBi Software so far there is no common respected evaluation category for the social dimension existing. The common basis for the social evaluation is the fulfilment of basic needs corresponding to the SA 8000 norm. Therefore the SLCA is not further addressed within the paper [10].

3 PROCEEDING

For the further evalution the balance shell is used as drawn in Figure1. The raw material extraction is respected by the use of life cycle inventory data within the GaBi software. The main focus of the modelling is the production phase of a product. Within this phase machining operations were analysed to identify all direct material and energy in and outputs. The following possible direct inputs were identified and modelled with parameters:

- Workpiece material
- Electrical energy
- Lightning
- Compressed Air
- Air Conditioning
- Exhaustion
- Lubricoolant
- Technical Cooling
- Technical Heating
- Heating
- Tools

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

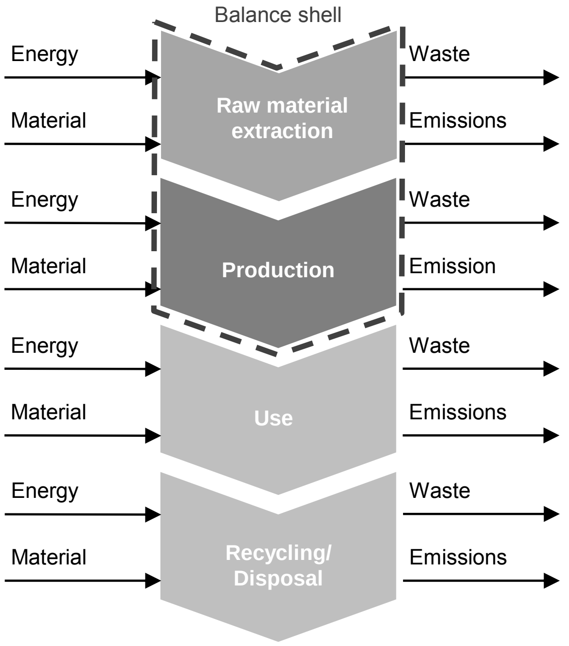


Figure 1: Balance Shell in the product life Cycle corresponding to [11][12].

Direct outputs of the machining process are:

- Product
- Emissions
- Waste for thermal use
- Waste for recycling
- Waste for disposal

These in and outputs were analysed and connected by functional units with the machining process. Also indirect inputs as e.g. the electrical energy for the production of compressed air are respected. The consumption of the single material and energy flows S_k can then be calculated corresponding to equation (1).

$$S_k = \sum_{i=1}^{n} \int^{t_i} \dot{S}_{k,i}(t)dt \qquad (1)$$

Within the single models parameters were used, which base on own measurements but should be adopted to the companies characteristics once. All material and energy flows were described with parametric models [13][14] and attributed to existing life cycle inventory data [12].

Only for the Wolfram Carbide (tools) and Krypton (Coating) no life cycle inventory data exist so far. Therefore approaches of Dahmus, Narita and Karpuschewski were taken for a assumption of the Primary Energy demand of the tool influence [15][16][17][18]. Therefore the category for the ecological evaluation is the Primary Energy, although the GaBi V5 Software allows much more categories. Intensive studies already demonstrated that the Primary Energy is a valid dimension for the overall ecological evaluation [19][20].

The use as well as the recycling and disposal phase are neglected within the evaluation, as the paper aims for the identification of the required material and energy for given tasks.

The cutting process is designed as a generic model which can be used for turning, milling, or drilling by using a switch.

Further on a few parameters (work piece geometry, material, used machine tool) have to be set to make a first assumption. Also detailed process parameters can be added to make a more valid calculation.

4 OPTIMISATION

For the energetic evaluation of cutting processes the specific cutting energy e_c is defined as the quotient of the cutting work W_e and material removal V_{cut}.[21][22][23][24].

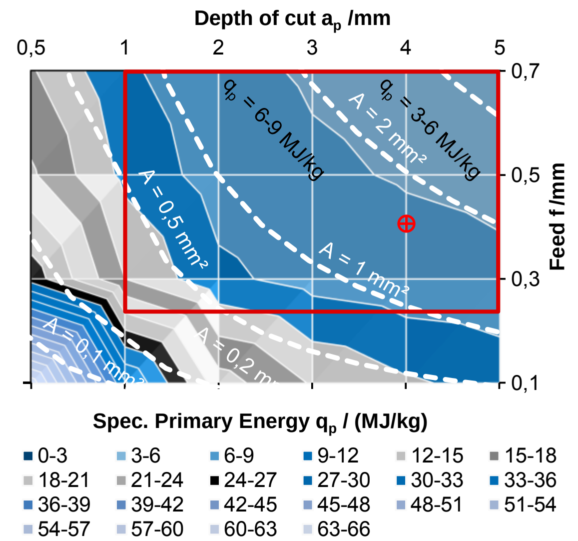
$$e_c = \frac{W_e}{V_{cut}} \qquad (2)$$

For the whole ecological evaluation the specific Primary Energy q_p is defined as the quotient of all Primary Energy demands $Q_{p,i}$ and the material removal m_{cut}.

$$q_p = \frac{\sum Q_{p,i}}{m_{cut}} \qquad (3)$$

The Primary Energy can be plotted depending on the process parameters. Within Figure 2 the specific energy is shown over the feed and the depth of cut. The red square marks the possible variation of the insert and the red bubble the preferred cutting conditions. It can be seen that within the possible process parameters the specific energy varies by the factor 5 to 6. It can also be seen that the cross section of cut corresponds very well with the contour line of the specific energy. With higher feeds and a bigger depth of cut the specific energy is falling. So far the simplified Taylor Equation (4) is used for the description of the tool life [25]. Therefore an influence of the feed and the depth of cut is neglected.

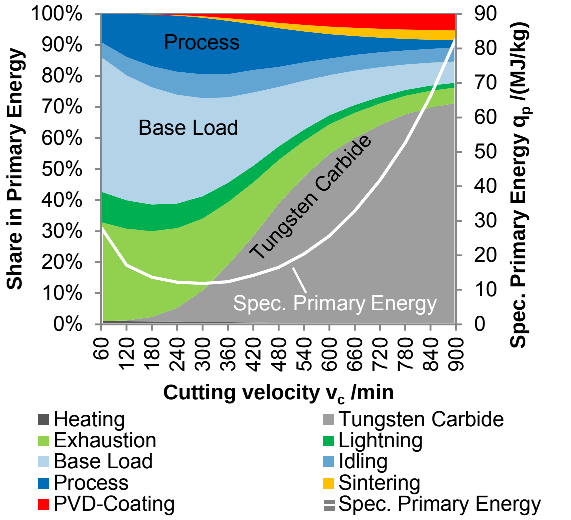
$$T = C_v \cdot v_c^k \qquad (4)$$



Process:	Turning	Processparameter	
Workpiece:	1.0503 (C45 E+N)	v_c	= 60 - 900 m/min
Lathe:	Index GU-800	a_p,	= 1,433 mm
Tool holder:	DWLNL 2525M08	f_z	= 0,3 mm
Insert:	WNMG040812	D_1:	= 49,83 mm

Figure 2: Specific Primary Energy of the turning process dependent on feed and depth of cut [12].

In Figure 3 the Specific Primary Energy is plotted as a white line over the cutting velocity. In the background the composition of the Primary Energy demand is shown in the background. While the base load and exhaustion is responsible for the Primary Energy demand at low cutting speeds the Tungsten Carbide is the main driver for high cutting speeds. Although the process load is rising with higher process parameters the influence on the Specific Primary Energy is falling with high process parameters again.



Process:	Turning	Processparameter	
Workpiece:	1.0503 (C45 E+N)	v_c	= 60 - 900 m/min
Lathe:	Index GU-800	$a_{p,}$	= 1,433 mm
Tool holder:	DWLNL 2525M08	f_z	= 0,3 mm
Insert:	WNMG040812	D_1:	= 49,83 mm

Figure 3: Specific Primary Energy of the turning process dependent on cutting velocity and origins [12].

Due to the different influencing factors on the Specific Primary Energy an local minimum can be identified by resolving equation (5).

$$0 = \frac{d\sum_{i=1}^{n} q_{p,i}(v_c)}{dv_c} \; and \; \frac{d^2\sum_{i=1}^{n} q_{p,i}(v_c)}{d{v_c}^2} > 0 \qquad (5)$$

A sensitivity analyses showed that the complete model is able to reach good results in identifying the optimal process parameters together with the belonging Primary Energy consumption, even if the assumptions for Tungsten Carbide and Krypton contain big errors. Only for high cutting velocities which are not relevant from the technical point of view, high deviations between the simulations can be seen.

5 DISCUSSION OF THE RESULTS

The parametrical model proved that the common assumption, that all cutting processes have a constant ecological impact which is independent from process parameters is wrong.

The simulation was also able to show the different influence of machine tools on the ecological impact, even if the process parameters were kept constant. To decide which machine tool should be used, also the costs have to be taken in account. A valid tool to compare different alternatives in these two dimensions is the LCC portfolio [26]. This allows comparing quantitative values in the dimensions Cost and Ecology. Nevertheless a common question is always rising. How can two different dimensions be compared and weighted? Or more practical: How much is one MJ Primary Energy worth in €?

Therefore a sustainability portfolio is proposed in the following. Basing on the LCC Portfolio the axis are scaled. Therefore a ratio was introduced. For this proposal it is assumed, that the minimum Primary Energy is required in the case, that a part or product can be used directly after the raw material extraction. This means the minimum required Primary Energy is in the material of the final product. The same assumption is taken for the dimension of the costs so that the best alternative can be chosen between different products or processes A, B, C ... , compare Figure 4.

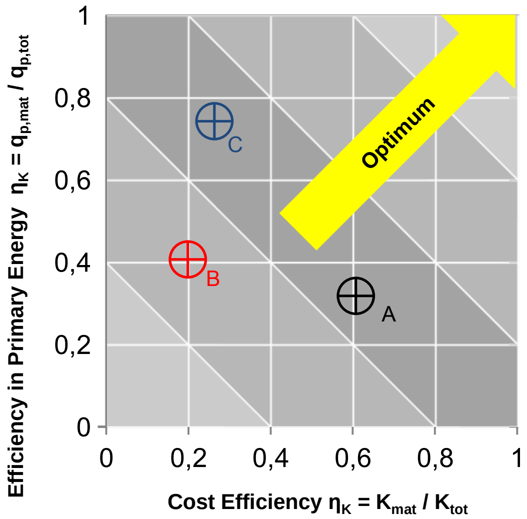


Figure 4: Specific Primary Energy of the turning process dependent on cutting velocity and origins [12].

6 SUMMARY

Within the paper an approach for the prediction of the sustainability of machining processes was shown. The results show in detail, that process parameters of cutting processes have an high influence on the Primary Energy Consumption and therefore also on their ecological impact. Detailed information on the modeling and results are recently published in [12].

Within the discussion of the results a further development of the LCC-Portfolio to a Sustainability Portfolio was presented which solves the problem of weighting two different dimensions.

7 ACKNOWLEDGMENTS

The author gratefully acknowledge the financial support of the Federal Ministry of Education and Research (BMBF) and the project supervision of the Project Management Agency Forschungszentrum Karlsruhe (PTKA-PFT) for the project BEAT (Assessment of the energy efficiency of alternative processes and process chains).

MANAGED BY

PTKA
Project Management Agency Karlsruhe
within Karlsruhe Institute of Technology

SPONSORED BY THE

Federal Ministry
of Education
and Research

8 REFERENCES

[1] Kara, S., Li, W., 2011, Unit process energy consumption models for material removal processes, In: CIRP Annals - Manufacturing Technology. Jg. 60, Nr. 1, S. 37–40.

[2] Seliger, G.: Aufbruch zu nachhaltiger Produktionstechnik. In: ZWF. Jg. 102, 2007, Nr. 4, S. 180-181

[3] Uhlmann, E.: Ressourceneffizienz in der Produktion. In: wt - Werkstattstechnik online. Jg. 98, 2008, Nr. 7/8, S. 524

[4] N.N.: Environmental management – Life cycle assessment – Principles and framework, DIN EN ISO 14040, November 2009

[5] N.N.: Environmental management – Life cycle assessment – Requirements and guidelines, DIN EN ISO 14044, Oktober 2006

[6] Herrmann, C.: Ganzheitliches Life Cycle Management. Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen. Habil.-Schr. Techn. Univ. Braun-schweig, Berlin: Springer, 2010

[7] Kuhrke, B.: Methode zur Energie- und Medienbedarfsbewertung spanender Werkzeugmaschinen. Diss. TU Darmstadt, 2011

[8] Herrmann, C.; Thiede, S.; Luger, T.; Zein, A.; Stehr, J.; Halubek, P.; Tomey, M.: Automotive Life Cycle Engineering. CIRP sponsored LCE Conference 2009, Cairo, Egypt, 2009

[9] Gerschwiler, K. et al.: Ressourcenschonende Produktion. AWK 2008 – Wettbewerbsfaktor Produktionstechnik, Apprimus Verlag, 2008

[10] Norm: SA8000: 2008. Social Accountability

[11] Schiefer: Entwicklung umweltgerechter Produkte. In: Hessen-Umwelttech News, 2009, Nr. 2, S. 15-16

[12] Schlosser, R.: Methodik zur Prognose der Nachhaltigkeit des Energie- und Stoffeinsatzes spanender Fertigungsprozesse. Diss. RWTH Aachen, Aachen, Aprimus (in publication)

[13] Klocke, F.; Schlosser, R.; Lung, D.: Energy and Resource Consumption of Cutting Processes. How Process Parameter Variations can Optimise the Total Process Efficiency. In: CIRP (Hrsg.): 17th CIRP International Conference on Life Cycle Engineering (LCE 2010). Anhui, China, 19.05-21.05.2010, S. 111 - 115

[14] Schlosser, R., Klocke, F., Lung, D., 2010, Sustainability in Manufacturing. Energy Consumption of Cutting Processes, In: Proceedings on the 9th GCSM conference. 22.-24.11.2010, Abu Dhabi, 22.-24.11.2010.

[15] Dahmus, J. B., 2004, An Environmental Analysis of Machining, In: Proceedings of IMECE2004. 2004 ASME International Mechanical Engineering Congress and RD&D Expo. Anaheim, California USA, November 13-19, ASME, 1–10.

[16] NARITA, H.; KAWAMURA, H.; NORIHISA, T.; CHEN, L.-y.; FUJIMOTO, H.; HASEBE, T.: Development of Prediction System for Environmental Burden for Machine Tool Operation. In: JSME International Journal Series C. Jg. 49, 2006, Nr. 4, S. 1188-1195

[17] Karpuschewski, B.; Kalhöfer, E.; Joswig, D.; Rief, M.: Energiebedarf bei der Herstellung von Hartmetall-Wendeschneidplatten. In: ZWF. Jg. 106, 2011, Nr. 09, S. 602-605

[18] Karpuschewski, B.; Kalhöfer E.; Joswig, D.; Rief, M.: Energiebedarf für die Hartmetallherstellung. In: ZWF. Jg. 106, 2011, Nr. 7-8, S. 496-501

[19] Huijbregts, M. A. J.; Rombouts, L. J. A.; Hellweg, S.; Frischknecht, R.; Hen-driks, A. J.; van de Meent, D.; Ragas, A. M. J.; Reijnders, L.; Struijs, J.: Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products? In: Environmental Science & Technology. Jg. 40, 2006, Nr. 3, S. 641-648

[20] Huijbregts, M. A. J.; Hellweg, S.; Frischknecht, R.; Hendriks, H. W. M.; Hun-gerbühler, K.; Hendriks, A. J.: Is Cumulative Energy Demand As Predictor for the Environmental Burden of Commodity Production. In: Environmental Sci-ence & Technology. Jg. 44, 2010, Nr. 6, S. 2189-2196

[21] Kronenberg, M.: Grundzüge der Zerspanungslehre. (Reihe: Mehrschneidige Zerspanung, Stirnfräsen, Bohren, Bd. 2). 2. Aufl. Berlin: Springer, 1963

[22] Wolfram, F.: Energetische produktbezogene Bewertung von Fertigungspro-zessen. Diss. TU Chemnitz, 1990

[23] Tönshoff, H. K.; Denkena, B.: Spanen. Grundlagen. 2. Aufl. Berlin: Springer, 2004

[24] Diaz, N.; Helu, M.; Jarvis, A.; Tönissen, S.; Schlosser, R.: Strategies for Minimum Energy Operation for Precision Machining. In: Machine Tool Tech-nologies Research Foundation (MTTRF) (Hrsg.): Proceedings of the MTTRF and ASCENTi-CNC ANNUAL MEETING 2009 July 8th and 9th in Shanghai. Shanghai, 08.-09.07.2009

[25] Taylor, F. W.: On the art of cutting metals. In: The American society of me-chanical engineers. New York, 1906

[26] Hunkeler, D. J.; Lichtenvort, K.; Rebitzer, G.: Environmental life cycle costing, Hoboken: CRC Press, 2008

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

8.5 A thermal analysis framework for cryogenic machining and its contribution to product and process sustainability

T. Lu, O. W. Dillon, Jr., I. S. Jawahir
Institute for Sustainable Manufacturing (ISM), University of Kentucky, Lexington, USA

Abstract

Cryogenic processing methods are environmentally-clean, toxic-free, and safe sustainable manufacturing processes, which also provide improved surface integrity, superior functional performance and greater product life in manufacturing processes. This paper presents a summary of findings from a preliminary study of the cryogenic cooling effects in a machining process. Various heat transfer scenarios need to be built into the model to consider the boiling phenomena. Cryogenic turning process includes a large radial thermal gradient in a thin layer of machined surface and changes the dynamic recrystallization process. A high speed, wide range temperature measurement system was developed, and preliminary experiments are carried out, investigating the contributing factors and the proper boundary conditions for modeling of cryogenic machining processes. The transition from slow cooling to a rapid cooling is observed.

Keywords:
Product/process sustainability, Cryogenic machining, Cooling, Boiling, Boundary conditions

1 INTRODUCTION

The most prominent issue in machining processes is the abundant, and often indiscriminate use of cutting fluids (CFs). Despite their anticipated benefits of better tool-life, better product quality and better chip evacuation, CFs overall have a negative impact on the economic performance of the process, the machine operators and the environment. The cost involved in the application of CFs is not limited to the purchased price paid, but also includes the cost involved in coolant system maintenance and treatment of used CFs, which takes up to 16% of the total machining cost [1][2]. Disposal of used CFs and emissions from the CF applications have potential hazardous impact on the environment. Contacting CFs and inhaling the airborne particles from coolant application could cause several different diseases [3].

These problems have over the years motivated researchers to find alternative techniques such as dry machining (cutting with no CFs) and minimal quantity of lubrication (MQL) machining. However, these more sustainable options can hardly provide sufficient cooling capability to replace the conventional CFs.

The cryogenic machining, which involves the use of cryogenic fluids such as the liquid nitrogen, is a competitive alternative. To make cryogenic machining a truly sustainable process, one must apply the coolant appropriately considering its cost and the embedded energy. While the sustainability performance of such a process could be assessed by a sustainability evaluation methodology [4][5], the parameter optimization requires a proper modeling of the process.

Despite its growing popularity in machining applications, in spite of the perceived difficulties in justifying the cost effectiveness, the exact cooling behavior due to cryogenic fluid application during the machining is not adequately understood. There is little known about the optimal use of cryogenic conditions for energy efficiency, operational effectiveness, product and process quality in terms of sustainability, etc. This paper presents a framework of heat transfer analysis of cryogenic machining from the sustainable manufacturing viewpoint. The fundamental theories of boiling heat transfer are introduced, followed by an experimental investigation applying high speed temperature measurement. Preliminary experimental results are shown to offer promising guidelines for future work.

With a proper understanding of the cooling effect in cryogenic machining, one could properly determine the optimal condition, including process parameters, coolant flow parameters and machine tool requirements, which would lead to optimized sustainability performance of the process regarding economic, environment and societal aspects.

2 BACKGROUND

2.1 Heat transfer in machining processes

Tool-life will heavily depend on the tool temperature [6], since high tool temperature usually leads to rapid tool-wear. Also, the high temperature of machined workpiece may have a negative impact on the product quality, such as softened material and poor accuracy. Many materials may show dynamic recrystallization during machining process [7]. This dynamic recrystallization will generate a surface layer with fine grains, which may be beneficial to the quality and performance of the manufactured product, ultimately producing more sustainable products. However, the high temperature on the workpiece surface in the machining process may activate grain growth, thus reduce or even eliminate the grain refinement effect. Therefore, it is very important to efficiently remove the heat generated in the machining process.

Heat transfer analysis due to cutting fluid applications in machining processes has been carried out by many researchers, such as Yue et al. [8] and Sun et al. [9]. These researchers considered conduction and convection heat transfer, and their focus has been on the fluid dynamics

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

around the cutting zone, including the rake and the flank regions [10]. In this paper, the focus is on the coolant application on the flank region, as it is considered most relevant to the dynamic recrystallization and grain growth suppression in the machined surface layer.

The temperature distributions in cryogenic machining were measured experimentally by embedding thermocouples into the workpiece or cutting tools [11]. The focus was on the material behavior and the cutting tool performance under cryogenic conditions, while the cooling effect is taken as a convection heat transfer process with a similar heat transfer coefficient as conventional flood cooling.

2.2 Boiling heat transfer

The saturation temperature of liquid nitrogen is -196°C at the pressure of one Bar (about 0.1MPa). Severe phase change, known as boiling, will occur when liquid nitrogen contacts the workpiece and the cutting tool, which may be at or above the room temperature. In practices, liquid nitrogen is usually stored in pressurized tanks. When released from pressurized vessel, the phase change may occur even before its physical contact with the workpiece and the cutting tool.

The famous Nukiyama Curve describing the boiling heat transfer [12] is shown in Figure 1 [13]. It is suggested that boiling will introduce a greater heat flux compared to convection heat transfer. Critical heat flux is reached when the vapor begins to cover the surface and to decrease the cooling efficiency.

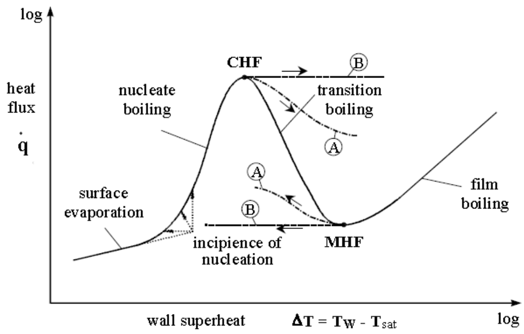


Figure 1: The Nukiyama Curve [13].

Such boiling heat transfer scenarios are well-studied in the field of controlled cooling of rolled metals. Some of the reported heat transfer data of hot plate cooled by water jets suggest surface heat transfer coefficient as high as 2×10^5W/(m^2°C) and cooling rate of 10~20°C/s [14]. Such values are around two orders of magnitude higher than the typical values used and found in other literatures in the machining area.

The time duration of the cutting fluid contact with the workpiece in cryogenic machining is very short compared to the controlled cooling of steel rolling. The exposure duration depends on the machining parameters and the size of the coolant coverage area. Combined with a high surface heat flux during this period, cryogenic application from the flank side would probably leave a shallow, but a much-cooled layer on top of the machined surface. After cooled zone exits the coolant coverage, the heat from the bulk part of the workpiece and the air will heat the cooled zone. The rapid cooling and heat-up processes on the boiling-cooled surface are observed in moving plate cooling experiments [14], as shown in Figure 2.

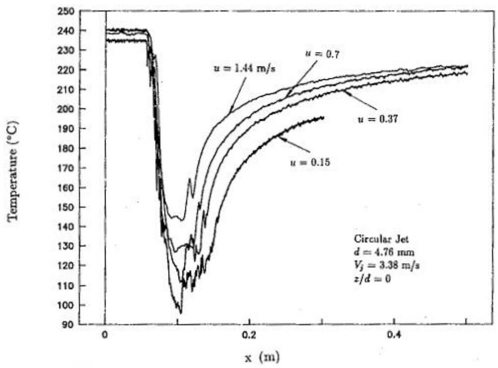


Figure 2: Measured plate surface temperature [14].

The control parameters influencing the heat transfer and the background mechanics for the case of controlled cooling of steel rolling are summarized as [14]:

- The flow rate or jet velocity: effect of flow pattern
- The fluid temperature: the effect of sub-cooling
- The surface temperature: the effect of superheating
- The speed of surface motion

In the case of cryogenic machining, the second parameter cannot be separately controlled. Experiments need to be designed to help understand the boiling heat transfer on the machined surface of the workpiece during cryogenic machining, in order to properly assess the cooling effect.

2.3 Sustainability concerns in cryogenic machining

Liquid nitrogen is environmentally clean, toxic-free and safe. It is favored from the environmental and societal aspect, as it does not pollute the environment or cast threat to operators' health. When machining hard materials, cryogenic machining often offer better tool-life and surface finish compared to conventional flood cooling and other coolant alternatives. Also, it has a great potential to improve the surface integrity of finished products with improved functional performance and/or greater product life [11].

On the other hand, due to the much higher price of liquid nitrogen compared to other coolant of same volume, the economic performance of cryogenic machining has been questioned. Furthermore, dimensional tolerances of machined product and frostbite threat are of concerns, too [15]. The advantages and concerns of cryogenic machining are summarized in Table 1 below.

Table 1: Reported advantages and potential disadvantages of cryogenic machining

	Reported Advantages	Potential Disadvantages
Cost	Higher cutting speed / better tool-life	Coolant cost
Product Quality	Better surface integrity	Dimensional accuracy
Environment / society	Clean operation environment	Frostbite threat

3 DESIGN OF EXPERIMENT SETUP

A significant effort is devoted to temperature measurement on liquid nitrogen cooled surface. At this preliminary stage, the focus is to build a valid temperature measurement system for the cryogenic machining scenario with a measurement tool described as follows.

3.1 Difficulties of temperature measurements in cryogenic machining

There were difficulties with the targeted measurements. First, the cryogenic temperature range limited the types of temperature measurement devices used. The thermocouples are chosen for wide temperature range coverage, but the working ranges involved is non-linear, thus simple integrated solutions are made impossible.

Another difficulty is the high cooling rate involved. The time of the cooling period will be in milliseconds. Infrared cameras on the market have a limited frame rate and a relatively long integration time. Several measurements of different temperature range taken to cover the wide temperature range would further degrade its performance over the dynamic target. While it is desirable to have a direct measurement of the entire temperature field, infrared cameras available now are not fast enough to capture the rapid temperature change it would have encountered under cryogenic machining conditions. The response time of thermocouples would depend on their bead size. Typically, the smaller the size is, the faster it would respond to the temperature change.

A further issue is the small scale involved. The material deformation zone and cutting region involved in machining are naturally sub-millimeter size. Also, due to the very short time involved, the cryogenically-cooled layer on the machined surface will be very shallow, which is estimated to be also sub-millimeter size.

3.2 Electronic system

The proposed solution is to use an ultra-thin thermocouple, coupled with a high bandwidth signal amplifier and a high speed data acquisition system. The captured voltage data will be mapped to the standard thermocouple table [16] to give the corresponding temperature reading, which will overcome the problem of non-linear behavior. The thermocouples used in experiments are Omega® CHAL-001 and CHAL-0005 K-type thermocouples, with a wire diameter of 25µm and 13µm, respectively. The bead diameters are measured to be around 60µm and 30µm, respectively. K-type thermocouple is selected due to its wide temperature range. The signal amplifier is based on Analog Devices® AD8421BRZ instrumentation amplifier, which gives a 3dB bandwidth of 2MHz at the gain of 100. The signal amplifier has a ±7V power supply unit built with voltage regulated from a lithium battery source and rail splitting circuits. The data acquisition unit used is National Instruments® NI USB-6366 USB-interfaced simultaneous data acquisition (DAQ) system, which provides a maximum sampling rate of 2MHz per channel. Matlab® codes are generated for data processing.

The DAQ system has a rated maximum noise of 1.3mV at the selected scanning range of ±5V. The power supply ripple noise is too low to be measured by the DAQ unit, as it is overwhelmed by the native noise of the DAQ unit. The circuit schematics of the signal amplifier is shown in Figure 3, though the components for the passive electromagnetic interference (EMI) filter are altered to permit a cutting frequency at 2.35MHz. The loaded noise recorded by the DAQ unit is 30mV peak-to-peak. The accuracy of the system is at worst around ±4°C. It should be noted that the electrical routing of the system is critical to its performance. Along with proper circuit routing, surface mounting devices (SMD) are used for the signal amplifier to achieve desirable performance. Shielded cables are used between each two devices of the system.

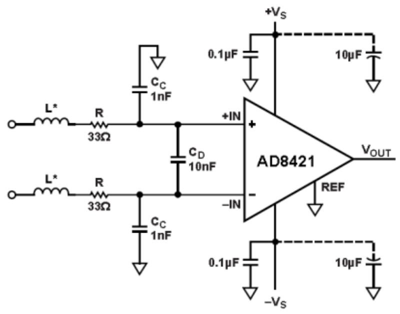


Figure 3: Signal amplifier circuit schematic [17].

Due to the small diameter, the thermocouple will show significant resistance, which is measured to be 670Ω for 25µm diameter thermocouple with 30cm leads and 1250Ω for 13µm diameter thermocouples with 20cm leads. To overcome the significant signal drifting introduced by the resistance, an amplifier chip with low offset voltage and small input bias current is needed, along with large current return resistors which are not shown in the schematics. This is one of the critical reasons why AD8421BRZ is chosen in this application. And, the commonly seen thermocouple breakage detection design is abandoned to reduce signal drifting. Also, care must be taken in not limiting the bandwidth due to the resistance of the thermocouple when designing the EMI filters.

3.3 Physical setup of preliminary tests

The two preliminary phases of the experiments on temperature measurement are on static surface. The liquid nitrogen jet is pumped from a 1MPa pressurized liquid nitrogen tank, and a plain round nozzle with an opening diameter of 3.18mm was used.

The first phase of the experiment is to test the capability of the high speed wide range temperature measurement system built, and was aimed at gaining some preliminary understanding of the boiling effects. The thermocouple is taped on a 1mm thick low density polyethylene (LDPE) strip, while the joint is exposed. The properties of common LDPE plastics [18] are summarized in Figure 4. The liquid nitrogen jet is aimed at 15° angle from the strip plain.

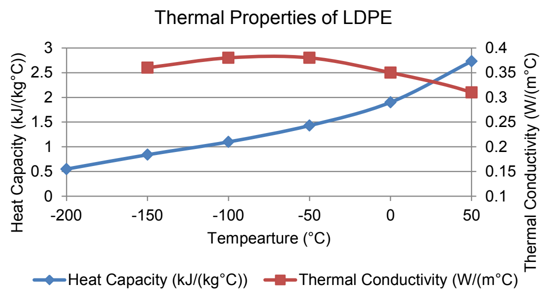


Figure 4: Common thermal properties of LDPE plastics [18].

The second phase of the experiments is on a *2011-T3* aluminum test block (specimen), and its dimensions are summarized in Figure 5.

The 12.7 mm diameter hole is used for clamping the test block. The small V-shape opening with a width of 4.75 mm and at an angle of 11° is to simulate the geometric features of TPG43X insert doing orthogonal cutting, which is the typical setup used in the lab [19]. The geometry of the upper surface is the same as the flank surface of the insert, and the lower surface of the opening is to simulate the machined surface on a workpiece. To embed the thermocouple, a micro groove is machined on the surface of the bottom block, facing the opening. It is 2 mm away from the tip of the opening. Its dimension is measured using a Zygo® white light interferometer. The groove is trapezoid shaped, with the opening size of 60 µm, the bottom size of 10 µm and the depth of 70 µm, as shown in Figure 6. Two larger notches are made at the groove edge end of the block.

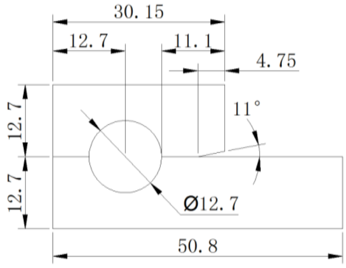


Figure 5: Dimensions of the aluminum test block, units in mm.

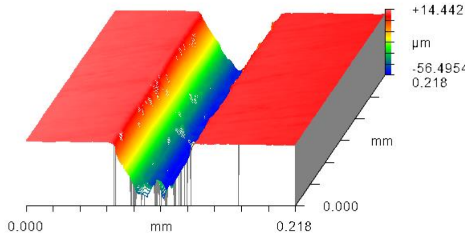


Figure 6: Measured groove dimensions.

The groove is filled with a thermal compound, which has a heat conductivity of 8.5W/(m°C). Then, the thermocouple is placed in to the groove by tensioning it with small downward forces around the two notches. Then, the setup is checked again to make sure the thermocouple is in place. It sits on top of the compound, slightly below the block surface. The bead is difficult to control and it may sometimes extend out of the groove, but within 20µm height, as shown in Figure 7.

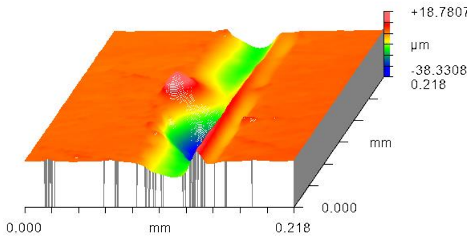


Figure 7: The bead extending out of the surface.

The liquid nitrogen jet is aimed at almost parallel to the lower surface of the V-shape opening. And, the nozzle tip is placed approximately 15mm away from the tip of the V-shape groove, which is the typical distance from the nozzle to the tool tip in flank-side cryogenic application of machining experiments.

4 PRELIMINARY EXPERIMENTAL RESULTS

The sample rate of data acquisition is 1MHz. The collected data are processed with Matlab® codes. Zero-drift compensation, cold joint compensation, moving average filtering of every ten samples and temperature mapping are performed in sequence. Each phase of experiments was performed five times. The results shown in the figures below are one of the five datasets, and the experiments showed good repeatability.

4.1 Results from the LDPE plastic strip

The measured surface temperature of LDPE plastic strip is shown in Figure 8.

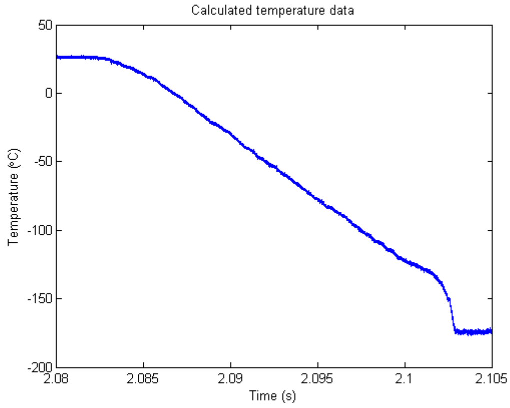


Figure 8: Measured temperature on the surface of LDPE under liquid nitrogen jet

It is interesting to find two distinguishing parts of the temperature curve. The stable part of the slow cooling section is taken out and least square polynomial fitting is applied. The data showed good fitting with 2nd order or above polynomial curves, as shown in Figure 9. The average cooling rate during this region is calculated by a first order polynomial fitting.

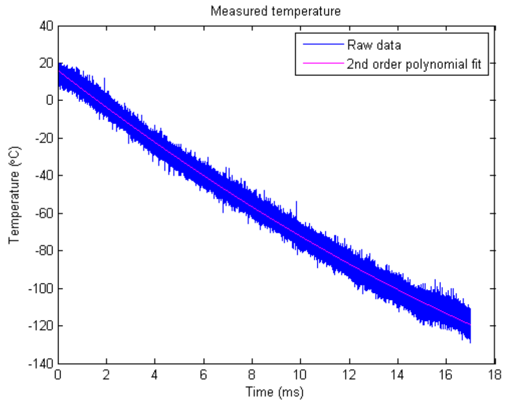


Figure 9: Temperature curve of the slow cooling region.

The stable part of the rapid cooling section is taken out and the above-mentioned process was applied, too. The results are shown in Figure 10. Summarizing the five data sets, the cooling rate of the slow cooling zone was 8.5±0.5°C/ms, and the cooling rate of the rapid cooling zone was 65±15°C/ms. The transition from slow cooling zone to rapid cooling zone occurs at -140±10°C. Stable temperature is -181±3°C.

Cooling rate within the rapid cooling section, and the transition temperature are not very stable among the five tests, but this agrees with the typical behavior of transition boiling.

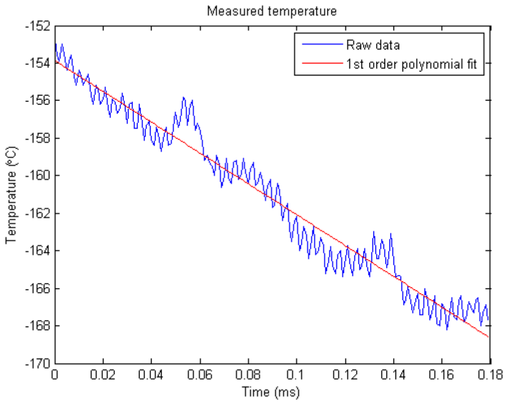


Figure 10: Temperature curve of the rapid cooling region.

4.2 Results from the aluminum test block

The measured surface temperature of aluminum test block which is described in detail in Section 3.3 is shown in Figure 11. The slow and rapid cooling sections are clearly identified. They are processed in a similar way as mentioned in Section 4.1. The measured cooling rate of the slow cooling zone was approximately 0.4±0.1°C/ms, and the cooling rate of the rapid cooling zone was 8.5±1.0°C/ms.

Condensed moisture forms water film and ice on the aluminum block surface. It was difficult to properly clean the test zone due to the congested geometry and fragility of the thin thermocouples. The measured results suggest cooling rate was one order of magnitude lower than the corresponding values shown in Section 4.1, for slow cooling and rapid cooling, respectively. This might due to the combined effect of altered geometry, different materials and moisture condensing, while only the first two are designed variables.

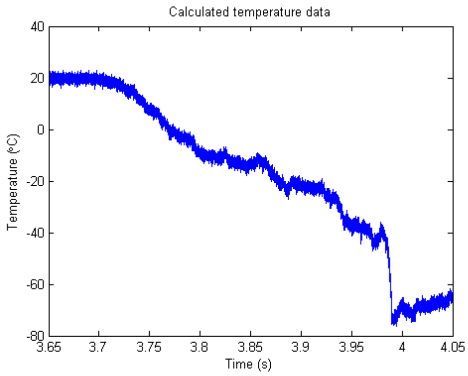


Figure 11: Measured temperature on the surface of aluminum test block under liquid nitrogen jet.

5 DISCUSSION AND FUTURE WORK

5.1 The heat transfer in cryogenic machining

A high speed wide range temperature measurement system is built and validated on two static scenarios. The two cooling sections with significantly different cooling rates suggest the transition from the initial film boiling to the developed transition boiling, and potentially nucleate boiling, which are described in the Nukiyama Curve. The findings can be summarized, for the cases of cryogenic machining with liquid nitrogen jet applied on the flank surface, as follows.

The heat transfer on the machined surface of the workpiece is significantly influenced by the surface temperature and ultimately the surface super heating. When the super heating is significant, film boiling occurs and the heat flux will be relatively low. And, when the surface is cooled down, transition boiling and nucleate boiling may occur, which introduce much higher heat flux. The moving workpiece is subject to cooling from liquid nitrogen flow for a very limited amount of time, and a higher heat flux is often preferred, judged according to the magnitude of cooling rate measured.

The low heat flux during film boiling is due to the separation of coolant and hot surface by the vapor film. Surface motion and certain flow pattern would help the coolant penetrate the vapor film. The future direction is targeted at finding proper parameters that could maximize the rapid cooling section during cryogenic machining.

Unlike the machined surface, the cutting tool is static and is exposed to coolant flow for a prolonged time. Its flank side surface temperature would be closer to the coolant temperature, thus the different superheating effects need to be considered in the thermal analysis.

5.2 An overview at the sustainability concerns

To achieve truly sustainable manufacturing in cryogenic machining applications, one must consider all the aspects involving both process sustainability and product sustainability, as summarized in Figure 12.

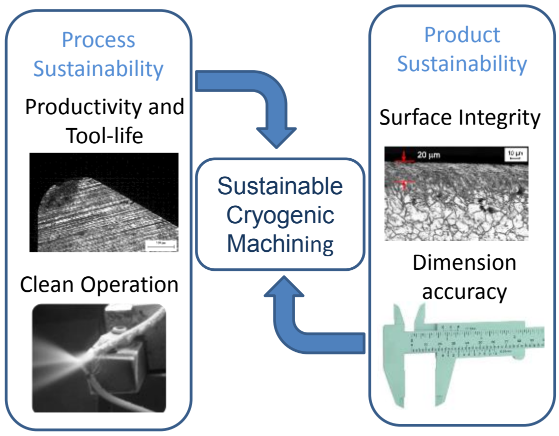


Figure 12: Achieving sustainable cryogenic machining.

As mentioned in Section 2.3, the major sustainability concerns of cryogenic machining are mostly due to the excessive use of liquid nitrogen. High flow rate of liquid nitrogen leads to a high consumption, which contributes to the problem of significant coolant cost. Instead of cooling the cutting zone only, the abundant amount of liquid nitrogen significantly reduces the temperature of the bulk part of the workpiece and the machine tool, causing dimension errors. Furthermore, the frozen workpieces and machine tools are at such a low temperature that they cannot be handled without proper protection equipment, and such low temperature is a frostbite threat to the operators. The splashing liquid nitrogen streams are also hazardous frostbite potentials.

These issues can be solved by a proper application of cryogenic machining. The part need to be cooled is only the cutting zone, which includes the tip of the cutting tool and the surface layer on the workpiece. Thus, cooling of other parts in the system could be considered as a waste. The preliminary study showed that the exposure time and flow conditions are the major influencing factors of the cooling capacity in cryogenic machining applications. Thus, it is implied that a redundant amount of cooling media is not necessary here.

This indicates the necessity of applying cryogenic machining in the way that only the necessary amount of coolant should be applied, in order to minimize its negative impacts in economic, environment and societal aspects. While only the sufficient amount of liquid nitrogen is supplied to the cutting zone, the total consumption of the costly coolant may be greatly reduced. And the splashing of the cryogenic flow will be minimized. The cooling of the bulk part of the workpiece and the machine tool could be greatly reduced, thus the dimensional accuracy and frostbite threat would not be a problem anymore. Instead, the product quality might be improved [7][11].

5.3 Future Work

With proper understanding of the cooling phenomena in cryogenic machining, one could properly set the flow rate and nozzles used. From the sustainability point of view, the application of a proper amount of liquid nitrogen could be achieved as opposed to using an excessive amount non-productively. And such a savings would benefit the manufacturing operations in implementing the cryogenic machining processes by making a convincing case for economic sustainability, in addition to the well-proven environmental and societal sustainability elements.

6 ACKNOWLEDGMENTS

The authors would sincerely appreciate Mr. Charles Arvin's help in preparing the experiments.

REFERENCES

[1] Byrne, G., Scholta, E., 1993, Environmentally Clean Machining Processes - A Strategic Approach, CIRP Annals Manufacturing Technology, 42: 471-474.

[2] Hong, S.Y., Zhao, Z., 1999, Thermal Aspects, Material Considerations and Cooling Strategies in Cryogenic Machining, Clean Technologies and Environmental Policy 1: 107-116.

[3] Sutherland, J.W., Kulur, V.N., King, N.C., Turkovich, B.F., 2000, An Experimental Investigation of Air Quality in Wet and Dry Turning, CIRP Annals Manufacturing Technology, 49: 61-64.

[4] Lu, T., Shuaib, M., Rotella, G., Feng, S.C., Badurdeen, F., Dillon, O.W., Rouch, K.E., Jawahir, I.S., 2013. Sustainability Evaluation of Manufacturing Processes Using a Metric-Based Process Sustainability Index (ProcSI): Part I: Development of a Comprehensive Methodology, Journal of Cleaner Production, submitted.

[5] Lu, T., Shuaib, M., Rotella, G., Feng, S.C., Badurdeen, F., Dillon, O.W., Rouch, K.E., Jawahir, I.S., 2013. Sustainability Evaluation of Manufacturing Processes Using a Metric-Based Process Sustainability Index (ProcSI): Part II: Method Applications and Validation. Journal of Cleaner Production, submitted.

[6] Oxley, P.L.B., 1989, The Mechanics of Machining: An Analytical Approach to Assessing Machinability, Ellis Horwood, Chichester.

[7] Umbrello, D., Rotella, G., 2012, Experimental Analysis of the Mechanisms Related to White Layer Formation during Hard Turning of AISI 52100 Bearing Steel, Materials Science and Technology, 28(2): 205-212.

[8] Yue, Y., Sun, J., Gunter, K.L., Michalek, D.J., Sutherland, J.W., 2004, Character and Behavior of Mist Generated by Application of Cutting Fluid to a Rotating Cylindrical Workpiece, Part 1: Model Development, Journal of Manufacturing Science and Engineering, 126: 417-425.

[9] Sun, J., Ju, C., Yue, Y., Gunter, K.L., Michalek, D.J., Sutherland, J.W., 2004, Character and Behavior of Mist Generated by Application of Cutting Fluid to a Rotating Cylindrical Workpiece, Part 2: Experimental Validation, Journal of Manufacturing Science and Engineering, 126: 426-434.

[10] Li, X., 1996, Study of the Jet-Flow Rate of Cooling in Machining Part 1. Theoretical Analysis, Journal of Materials Processing Technology, 62: 149-156.

[11] Hong, S.Y., Ding, Y., 2001, Cooling Approaches and Cutting Temperatures in Cryogenic Machining of Ti-6Al-4V, International Journal of Machine Tools & Manufacture, 41: 1417–1437.

[12] Nukiyama, S., 1966, Maximum and Minimum Values of Heat Q Transmitted from Metal to Boiling Water under Atmospheric Pressure, International Journal of Heat Transfer, 9: 1419-1433.

[13] Auracher, H., 2003, Some Remarks on the Nukiyama Curve, JSME TED Newsletter, 41.

[14] Chen, S., Tseng, A., 1992, Spray and Jet Cooling in Steel Rolling, International Journal of Heat and Fluid Flow, 13(4): 358-369.

[15] Yasa, E., Alpagan, U., Pilatin, S., Colak, O., 2012, A Review on the Improvements in Machinability of Ti-6Al-4V, Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey, Oct 30 - Nov 2, 790-795.

[16] National Institute of Standards and Technology, 2012, NIST ITS-90 Thermocouple Database, available at: http://srdata.nist.gov/its90/main/its90_main_page.html

[17] Analog Devices, 2012, AD8421: 3 nV/√Hz, Low Power Instrumentation Amplifier Data Sheet, available at: http://www.analog.com/static/imported-files/data_sheets/AD8421.pdf

[18] Martienssen, W., Warlimont, H., 2006, Springer Handbook of Condensed Matter and Materials Data, Springer, New York.

[19] Rotella, G., Lu, T., Settineri, L., Jawahir, I.S., 2012. Machining of AA7075 Aluminum Alloy: a Process Optimization for Sustainability. Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey, Oct 30 - Nov 2, 501-506.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

8.6 Experimental Study of Micro-holes Position Accuracy on Drilling Flexible Printed Circuit Board

L. J. Zheng[1], X.Zhang[1], C. Y. Wang [1,*], L. F. Wang[1], S. Li[1], Y. X. Song[1], L. Q. Zhang[2]
[1] Guangdong University of Technology, Guangzhou 510006, China
[2]Shenzhen LiuXin Industrial Co., LTD, Shenzhen 518000, China

Abstract
Drilling through holes is an important procedure in the manufacturing process of flexible printed circuit board (FPCB). The main influencing factor of micro holes quality is holes position accuracy. Holes position accuracy directly influences the FPCB electrical performance, reliability and the realization of the installation requirements. Therefore, it is very necessary to analysis the influencing factors of holes position accuracy. In this paper, single factor experiment method is used to study the relation of holes position accuracy and those influencing factors, obtaining the influence law of each factor on the holes location accuracy. The accuracy will get better with the increasing of spindle speed, retraction speed and drill diameter，however the accuracy will get worse with the increasing of thickness of entry board and number of FCCL stack. Choosing appropriate entry board use-pattern will greatly improve the holes position accuracy.
Keywords: micro-holes, position accuracy, high speed, micro-drill, FPCB

1 INTRODUCTION

With the development of electronic devices and communications tools tends to be more shorter and more thinner, Printed circuit board (PCB)， as the carrier of the electronic devices，also tends to the high-rise, high-density, micro-holes and fine lines. Then a higher requirement of micro-drilling, which is the most basic and necessary process in the production of PCB, has been proposed. Flexible printed circuit board(FPCB) is a promising branch of printed circuit board industry, which is developing rapidly. It should be always seeking a perfect solution to electronic packaging needs for its highly reliable, perfect flexible. It leads the electronic packages to smaller, lighter and more functional. So it has been abundantly used in the aerospace, military, mobile communication, digital cameras and other fields.

In general, after the micro-hole is drilled in the FPCB, a cleaning and desmearing processes is performed followed by a two-step copper deposition. Quality holes are ones in which the deposited copper layer can be connected stably at each layer of circuit with repeated thermal shock. One or more holes lose effectiveness can make the whole circuit even the electrical appliance stop working.

A flexible printed circuit board usually consists of a conductive material layer of traces bonded to a dielectric layer. Copper is a very common metal as the conductive material layer. The dielectric layer is usually polyimide or polyester. Usually an adhesive is used to bond the conductive material layer to the dielectric layer. Micro-hole is an important part of the flexible printed circuit board, the process of micro-drilling is one of the problems of the PCB manufacturers' production. However, it's not easy to control the quality of the production process of micro holes. One of the most important influencing factors of micro holes quality is holes position accuracy. With the influence of the drill bits and equipment, hole shift occurs easily in micro-drilling. Holes location accuracy directly influences the electrical performance, reliability and the realization of the installation requirements about FPCB. So holes location accuracy is always the most important control point in the manufacturing process of FPCB [1-6].

The author's research group had published several papers in this area. Huang [7,8] studied the conventional drilling of PCBs and the mechanism of the creation of the holes using finite element technology. Yang [9] studied chip morphology when drilling a 3.2 mm hole in PCBs and found that the chips from the resin/glass fiber cloth layer were continuous chips with five different morphologies. Tang [10, 11] studied a high-speed drilling machine suitable for PCBs with 0.1-mm-diameter micro holes. The machine had functions that can measure the drilling force. Tang also published an introduction to the simulation of ultra-high-speed drilling of the copper foil layer of PCBs using the finite element method (FEM). A complete review of drilling PCBs had been performed as well [12].

Studies of micro holes location accuracy were always focused on rigid board on the printed circuit board industry before. The research of how to improve the drilling quality of flexible printed circuit board effectively dose not have a detailed experimental study so far. Tang [13] studied the influence factors of holes location accuracy such as vibration in micro-drilling process, micro-drill diameter and micro-drill wear, and found that the holes location accuracy increased with the increasing of the bit diameter, decreased with the increasing of vibration acceleration and micro-drill wear. Watanabe [14] did experiment in the spindle speed of 300 krpm with 0.1 mm diameter micro-drill to study the relationship between the bit radius run-out and micro-holes surface quality, and found that the drill point swing radius have a certain influence on the hole position accuracy and surface roughness. Zheng [15] studied that the wear of micro-drill, increase of feed speed and spindle speed which will lead the holes position accuracy of rigid-PCB get worse. Zheng [16] found that the resin adhered to the tip would influence the accuracy of the micro-holes location.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

In this paper, as a part of a large research project on FPCB micro-drilling, several experimental tests were conducted to study micro-holes position accuracy when drilling FPCBs. It was important to study micro-holes position accuracy during the FPCB drilling process as part of hole quality. The drilling process was photographed and the CPK(Complex process capability) was measured and analyzed according to the test results. The influence of drilling conditions (spindle, feed and retraction speed) and wear of micro-drill on the CPK were also been studied.

2 THE INFLUENCE MECHANISM OF HOLE LOCATION ACCURACY

In the FPCB micro hole drilling process, cutting force and torque will be formed, and the cutting force can be decomposed into XYZ three directions. The size of these forces depends on the geometry of the micro-drill, property of printed circuit board (such as workability, vertical plate surface roughness) and drilling process parameters (spindle speed, feed rate, retraction speed, cover plate combination).

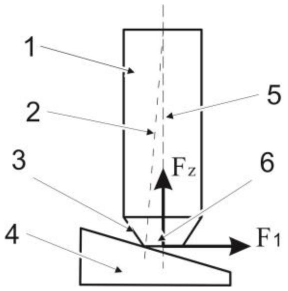


Figure 1: Changes of rotary centerline and the force of drill tip

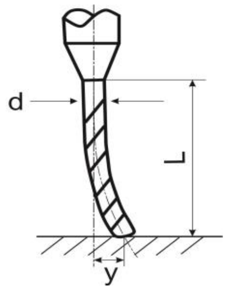


Figure 2: Drill positioning diagram

When the micro drilling of the flexible printed circuit board began, as the chisel edge of the drill bit just came into contact with the surface of FPCB, if the drill chisel edge area is relatively large, it will produce a large lateral force F1 (the resultant force of x and y direction), it will deflect the tip of the drill and cause drill tip slipping. The result is that the drilling position of micro hole generates a random displacement, so that the drilling process would not be carried out in accordance with predetermined position. When the surface of the sheet being drilled inclined or uneven, this effect will be more significant. As is shown in Fig. 1 the surface of a sheet being drilled inclined at a predetermined angle, the chisel edge sharp corners come into contact with the sheet, the micro-drill's axis of rotation will be deflected.

When the cutting edge of micro-drill starts cutting, the chip will also impact the motion direction of the micro-drill. With the drill drilling into the plate, the drill would be bending as is shown in Fig. 2. The bending of the drill bit will generate a bending moment, bending moment from the drill's tendency to return to its starting position, and thus cause roundness error as the drill bit drilling into the FPCB.

3 TESTING EQUIPMENT AND CONDITIONS OF MICRO-DRILLING

3.1 Testing equipment and workpiece

The micro-drilling processes were performed on a Hitachi MARK-16 drilling machine with a spindle speed of up to 160 krpm. The measurement of hole position accuracy was performed on a hole-bit precision measuring instruments named PM-2824 Hole Inspector. The schematic of the experimental setup was shown in Fig. 3.

(a) Hitachi 6 axis (160 krpm) (b) PM-2824 Hole Inspector

Figure 3: Testing equipment

The workpiece was SF305 flame-resistant type polyimide film based flexible copper clad laminate (Double side) made by Guangdong Shengyi SCI Tech Co., LTD. The structure of the SF305 was shown in Fig.4. It is 101 μm in thickness, laminated by polyimide (PI) film of 25 μm. Both sides are clad with a copper foil of 18 μm thickness. Among polyimide (PI) film and copper foil is adhesive of 20 μm thickness.

Figure 4: Structure chart of flexible double-sided copper clad laminate

The entry board in this paper have two types: Cold shock （LC-110） entry board and MVC lubrication aluminum. The backing board was phenol formaldehyde plate (FZ-120). The entry board and backing board were both made by Shenzhen LiuXin industrial Co., LTD. The basic parameters of the entry board and backing board were shown in Table 1.

Table 1 Physical performance of Entry Board and Backing Board

Physical performance	LC-110	MVC	FZ-120
Physical shape			
Thickness	0.3/0.5/0.8 mm	0.16 mm	1.5mm
Thickness Tolerance		±0.1mm	
Warpage(Diagonal length)	Less than 0.3mm		Less than 0.6mm
Dimensional tolerances		±3mm	
Density	----------		1300-1450 kg/ m³
Surface conditions	Smooth	Smooth	Smooth

All cemented acrbide micro-drills(6-9% Co and 91-94% WC; vickers hardness 1750-2150HV30) were made by Shenzhen Jinzhou Precision Technology Corporation and have diameters of 0.15 mm,0.25 mm,0.35 mm. The structure of the micro-drills are shown in Fig. 5.

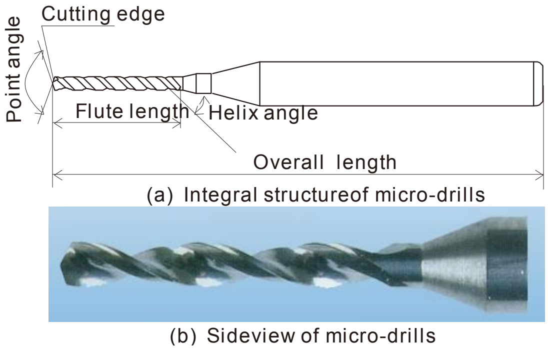


Figure 5: Structure of micro-drills

3.2 Drilling conditions and evaluation index of hole position accuracy

In the drilling experiments, the feed rate , the spindle speed the combination of entry board and backing board were carried as shown in Table 2.

In this paper, CPK (Complex process capability) index was used to evaluate the accuracy of the holes position. CPK refers to the degree of the ability of the process to meet product quality standards (e.g. specifications, range, etc.). The greater the value of CPK is, the better the quality of the holes position accuracy is. The schematic of CPK measurement is shown in Fig.6.

Table 2. Drilling conditions

Parameters	Diameter of drills (D) (mm)		
	0.15	0.25	0.35
Spindle speed (n) (krpm)	100-158		
Feed rate (v_f) (mm/s)	15-50		
Retraction speed (v_r) (mm/s)	100-300		
Number of drilled holes	1000, 2000, 3000		
LC-110 thickness (mm)	0.3, 0.5, 0.8		
Entry board use	No entry board, LC-110, MVC+LC-110		
Stack of board layers	3		
Environmental temperature	22 ℃		
Relative humidity (%)	66		

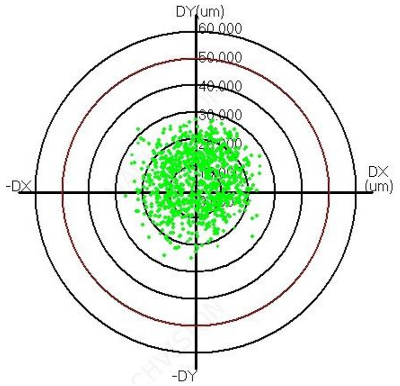


Figure 6: Photographs of CPK measurement

4 RESULTS AND DISCUSSION

4.1 The surface topography of micro-hole under different drilling depth taken by SEM

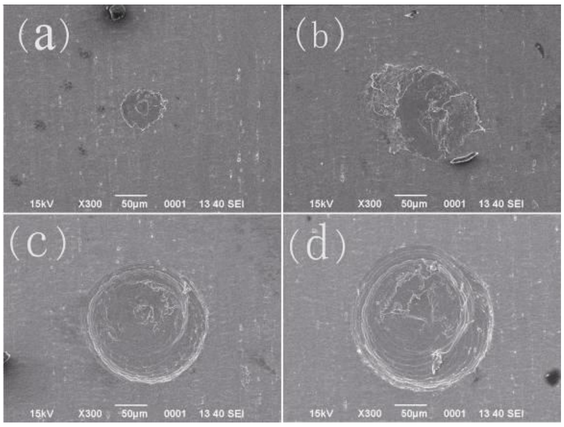


Figure 7: Surface topography of micro-hole under different drilling depth(Drill depth :a=20 μm, b=40 μm, c=60 μm, d=80 μm, D=0.25mm, v_f =50 cm/min, n=140 krpm, v_r=300 mm/s)

Figure 7 shows the surface topography of micro-hole with different drilling depth. It is shown in Fig. 7 (c) and Fig. 7 (d) that a partiality phenomenon of the drill occured as the drilling depth increased during drilling FCCL. The main reason may be the unbalance force of the drill taken by the unsuitable drilling parameters or the surface of FCCL is not flat or even enough.

4.2 The influence of the main drilling parameters on holes position accuracy

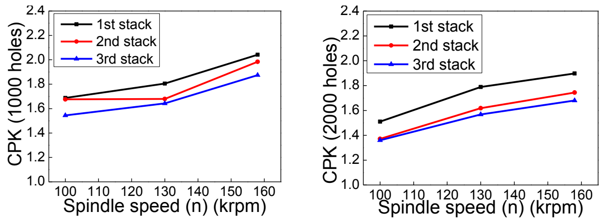


Figure 8: Influence of spindle speed on CPK（D=0.25 mm, v_f=30 mm/s, v_r=300 mm/s）

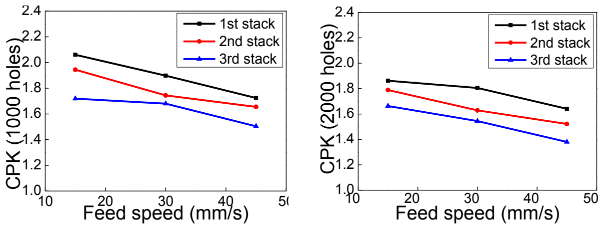


Figure 9: Influence of feed speed on CPK（D=0.25 mm, n=158 krpm, v_r= 300 mm/s）

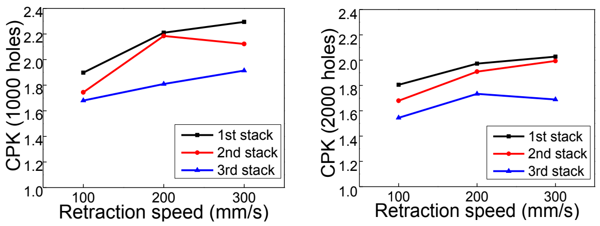


Figure 10: Influence of retraction speed on CPK（D=0.25 mm, n=158 krpm v_f=30 mm/s）

Figure 8, 9, 10 showed the influence of the main drilling parameters (spindle speed, feed speed, retraction speed) on CPK. In Fig. 8, it can be seen that when the drilling speed changed from 100 krpm to 158 kprm, in every stack, the CPK increased as the spindle speed's increased. In Fig. 9, it can be seen that when the feed speed changed from 15 mm/s to 45 mm/s, in every stack, the CPK decreased as the feed speed increased. It was thought that this may due to the thickness of material removal per revolution would affect the force status of the tip of micro-drill. The more thickness the material removal per revolution was, the more unbalanced the force acting on the micro-drill. Therefore, the increase of spindle speed equaled the decrease of the thickness of material removal per revolution, the increase of feed speed equaled the increase of the thickness of material removal per revolution.

In Fig. 10, it can be seen that when the retraction speed changed from 100mm/s to 300mm/s, in every stack, the CPK increased as the retraction speed's increases. It was thought that this may due to that the diameter the micro-drill was small and there will adhesive drilling chips in the spiral groove inevitably, which makes the drill tip have a unstable stress in high speed rotation will affect the accuracy of hole position. When the retraction speed increased, the time the unbalance force affected the accuracy of the hole position would be shorted. Therefore, the accuracy of hole position will improve when the speed of drill retraction increases.

4.3 The influence of micro-drills on holes position accuracy

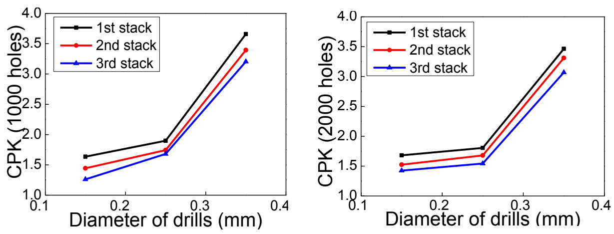


Figure 11: Influence of diameter of drills on CPK（n=130 krpm, v_f=30 mm/s, v_r=300 mm/s）

One of the most important factors for the hole-position accuracy of PCB is the rigidity of micro-drill, which may increase by a trend of the drill diameter. It is shown at the Fig. 11 about the situation of flexible double-sided copper clad laminate. The hole-position accuracy will increase when the diameter of the drill bit increases. The CPK can reach above 3.0 as a superior rank, when a 0.35mm-diameter drill was used in the same process of drilling.

4.4 The influence of number of drilling holes on holes position accuracy

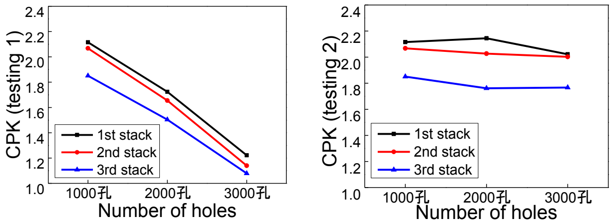


Figure 12: Influence of number of drilling holes on CPK（D=0.25 mm, n=130 krpm, v_f=30 mm/s, v_r=300 mm/s,）

A trend of influence between the amount of drilling holes and the hole-position accuracy is shown at Fig. 12. The hole-position accuracy will decrease when the amount of drilling holes increases. It was due to the wear of the drill. The cutting blade will be more and more dulled and compared with a new one, the accuracy may drop down for the reason of offset of the drill point. As the chips may be stuck on the dulled cutting blade during drilling FCCL, the performance of chip removal may decline, with worse and worse roughness of hole-wall and position accuracy.

4.5 The influence of entry board use on holes position accuracy

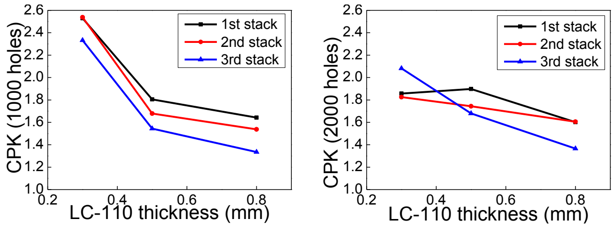


Figure 13: Influence of thickness of entry board on CPK（D=0.25mm, n=130 krpm, v_f=30 mm/s, v_r=300 mm/s,）

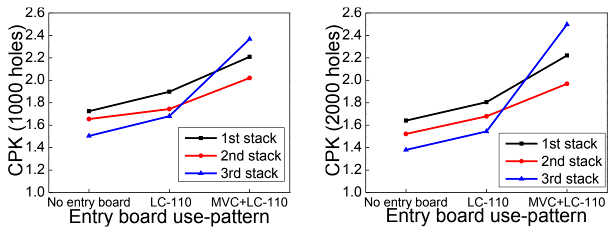


Figure 14: Influence of use-pattern of entry board on CPK（D=0.25 mm, n=130 krpm, v_f=30 mm/s, vr=300 mm/s）

Figure 13 shows the influence of thickness of entry board used in micro-hole drilling on CPK. It can be seen that the value of CPK decreased with the increase of the thickness of entry board. It was because that the drill may be mildly deflect unavoidably for many reasons during the drilling operation. Once it drills slantingly, the situation will get more deteriorated. It led to the decline of the hole accuracy. Thus, the value of CPK decreased with the increase of thickness of entry board.

Figure 14 shows the influence of use-pattern of entry board on CPK. It can be seen that among three use-pattern of entry board, the value of CPK was the largest when the use-pattern of entry board was ‘MVC+LC-110’, and when the micro-drill drilling without entry board, the value of CPK was the smallest.

5 CONCLUSIONS

To study the hole position accuracy of FPCB micro-drilling, the CPK (Complex process capability) was measured. The factors affecting micro-holes position accuracy was studied. The results can be summarised as follows:

(1) The value of CPK will increase with the spindle speed, retraction speed and drill diameter. And it will decrease with the increase of the feed speed, the number of drilled holes and the thickness of entry board.

(2) The use-pattern of entry board will influence the value of CPK. Choosing a suitable use-pattern will improve the hole position accuracy. In the process of micro-drilling, make the MVC lubrication aluminum upon the LC-110 as a use-pattern will obtain a higher holes position accuracy and avoid inlet burrs produced at the same time.

(3) The stacks of FCCL in drilling process had impact on hole position accuracy. The more the stacks was, the lower the value of CPK was.

6 ACKNOWLEDGMENTS

This study was supported by National Natural Science Foundation-Guangdong Province Foundation, China (No. U0734007), the Guangdong Economic &Information Commission Modern Information Services Project (No. JGZB2010ZZHCT027), the Program of China Postdoctoral Science Foundation (No. 2012M521574) and the Special Foundation of China Postdoctoral Science (Grant No. 2013T60789).

7 REFERENCES

[1] C.Y. Wang, L.X. Huang, L.J. Zheng, et al. Review of Micro-drilling PCB & Key Technology, Tool Engineering, Vol.44(2010),No.1,pp3-10. (in Chinese)

[2] X. Zhang, C.Y. Wang, L.J. Zheng, L.F. Wang. Experimental study on cutting force of high-speed micro-drilling flexible printed circuit board. Materials Science Forum, v 723, p 401-406, 2012, High Speed Machining V

[3] H. Nakagawa, K. Ogawa, A.Kihara, T.Hirogaki. Improvement of micro-drilled hole quality for printed wiring boards. Journal of Materials Processing Technology. Vol. 191 (2007), p. 293–296

[4] L.J. Zheng, C.Y. Wang, L.P. Yang, Y.X. Song, L.Y. Fu. Characteristics of chip formation in the micro-drilling of multi-material sheets. International Journal of Machine Tools & Manufacture, Vol. 52, No. 1(2012), p. 40–49

[5] Y.S. Xu, J.M. Mao, Y.M. Chen, W. He. Study on process of NC drilling for FPCB. PRINTED CIRCUIT INFORMATION, No. 10(2010), p. 28-30

[6] Eiichi Aoyama, Hiromich Nobe, Toshiki Hirogaki. Drilled hole damage of small diameter drilling in printed wiring board. Journal of Materials Processing Technology. No. 118(2001), p. 436-441

[7] L.X. Huang, C.Y. Wang, M. Chen, X.H. Zheng, Simulations and experiments on drilling PCB based on thermo-mechanical coupling, in: Proceedings of the Advances in Manufacturing Technology XXIV, ICMR2010, 2010.

[8] L.X. Huang, Research on Fixed Hole Drilling on Printed Circuit Board, Ph.D Dissertation, GDUT, China, 2011 (in Chinese).

[9] L.P. Yang, L.X. Huang, C.Y. Wang, Drilling force and chip morphology in drilling of PCB Supported hole, Advanced Materials Research 188 (2011)429–434.

[10] H.Q. Tang, C.Y. Wang, B. Wang, etc., Module partition and application for printed circuit board high speed drilling machine, Advanced Materials. Research 188 (2011) 104–109.

[11] H.Q. Tang, J. Wen, C.Y. Wang, Simulation of drilling on the copper of PCB with ultra-high-speed, Advanced Materials Research 188 (2011) 739–742.

[12] L.J. Zheng, C.Y. Wang, Y.X. Song, L.P. Yang, Y.P. Qu, P. Ma, L.Y. Fu. A review on drilling printed circuit boards. Advanced Materials Research. Vol. 188(2011), p. 441-449

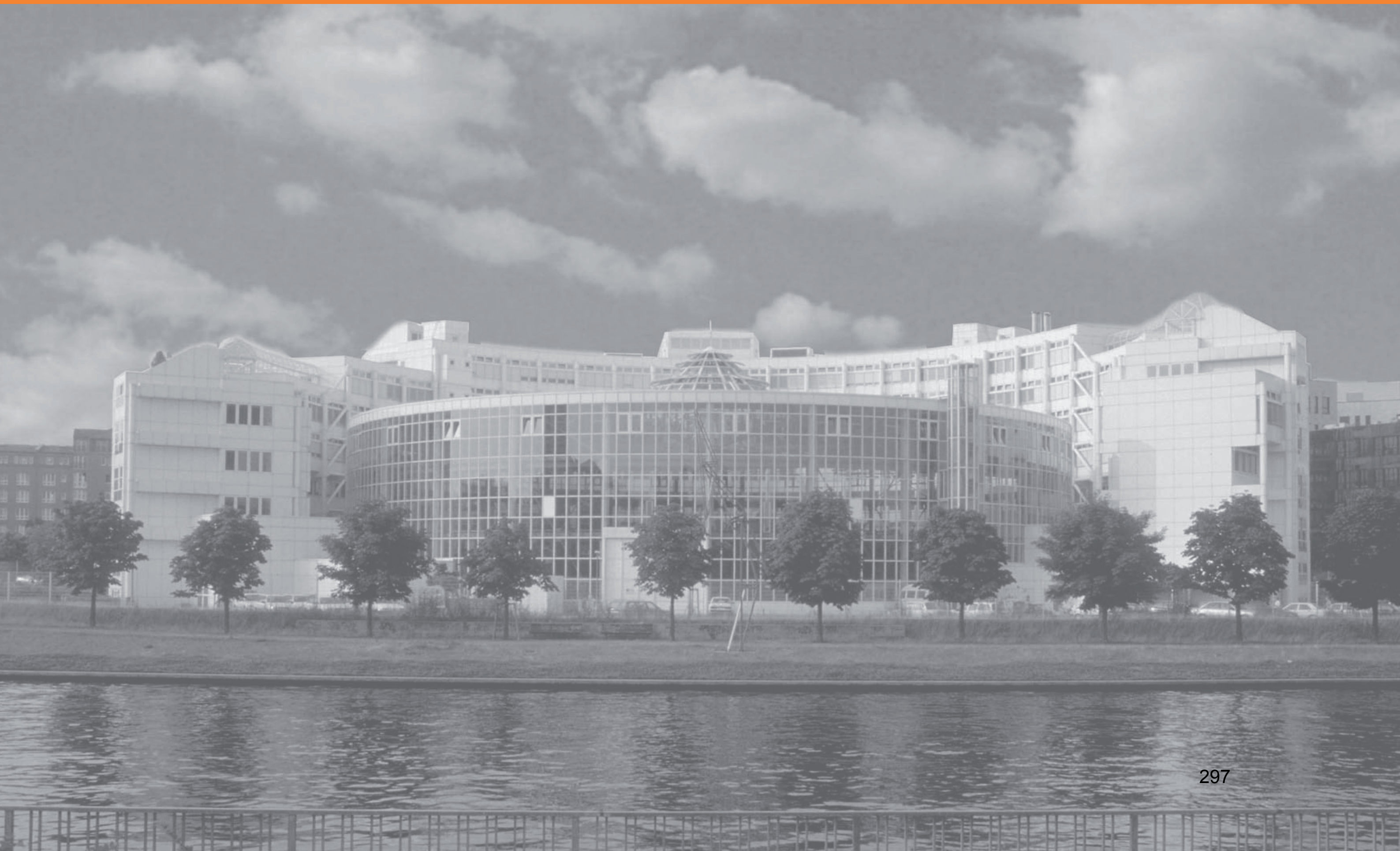
[13] H.Q. Tang, Dynamic Characteristics of Micro-drilling on Printed Circuit Boards(D), Guangzhou, Guangdong University of Technology,2012 (in Chinese)

[14] Watanabe H., Tsuzaka H., Masuda M.. Microdrilling for printed circuit boards (PCBs) - Influence of radial run-out of micro-drills on hole quality[J]. Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology, 2008, 32(4): 329-335.

[15] L.J. Zheng, Micro-holes Drilling Mechanism of Printed Circuit Boards(D), Guangzhou, Guangdong University of Technology,2011 (in Chinese)

[16] L.J. Zheng, C.Y. Wang, L.Y. Fu. Wear mechanisms of micro-drills during dry high speed drilling of PCB, J Mater Processing Tech. 212 (2012) 1989-1997.

Session 9
Implementations



GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

9.1 The slow factory: a new paradigm for manufacturing

G. Campana [1], B. Cimatti [2]
[1] CIRI MAM, Interdepartmental Centre for Industrial Research, University of Bologna, Italy
[2] Institute for Higher Studies, University of Bologna, Italy

Abstract
The current industrial system is generally based on highly automated manufacturing plants, which allow fast production and serial manufacturing. However, some Italian entrepreneurs, using their expertise and know-how, have decided to recover the value of tradition and craftwork and are finding that slow working processes can produce positive results and add distinctive value to a product. Similar cases are recognizable all around the world and in different industrial fields; in particular slowness in the food industry is of great significance.
Slow Manufacturing can increase the quality of the product, giving the uniqueness and excellence that attracts the most demanding of customers. Traditional machines can be fitted in order to assist modern automatic equipment and skilled workers can thus perform semi-automatic processes in order to obtain appealing high-caliber goods. Technology returns to being predominantly mechanical. The reduction of electronics and computerization, the elements largely responsible for standardization, allows the skills of the craftsman to once again become relevant.
Keywords:
Craftsmanship, Made in Italy, Manufacturing, Slowness, Sustainability

1 INTRODUCTION

Manufacturing is the driving force of the European community, providing more than 30 million jobs and contributing over 6,500 billion Euros in gross domestic product (European Commission 2013). Consequently, industrial leadership is one of the main targets of current European framework programs and the support of industrial innovation and development is always one of the main concerns of national and regional governments across Europe.

Italy has shown significant economical growth since the Second World War predominantly based on manufacturing activities, specializing in traditional sectors and obtaining a good ranking in the international market for products such as garments and furniture. The term “Made in Italy” indicates the artisanal and industrial products generally related to four sectors: Fashion/Textiles; Furniture/Interior Design; Food/ Beverage; Automation/Mechanics. The first three refer to traditional productions, while the fourth involves advanced technology and derives from the need of equipment to manufacture the traditional products. Made in Italy production corresponds to over 65% of Italian manufacturing activity. Many factories are located in industrial clusters: territorial concentrations of interconnected medium-sized enterprises - a chain of production - involved in similar activities. At present, 223 clusters are recognized in Italy, for historical and geographical reasons each one originated from a specific vocation of the territory towards a particular production. This industrial system has for years maintained a high ranking within the most industrialized eight countries and made Italian products internationally esteemed. Made in Italy is a sign of quality and prestige, evoking the idea of good taste together with careful attention to every detail of the product.

Recently, the internationalisation of production has led to the possibility to manufacture products in developing countries where the cost of labour is lower than in Italy. As a result, many European industries have established production plants in low-cost workforce countries, assembling parts and components from all over the world in order to achieve the optimum balance between quality and cost. The development of emerging countries such as Brazil, Russia, India, China and South Africa - the so called BRICS - has determined an increase in worldwide competition in the field of manufacturing by threatening the economic leadership of many industrialized countries, forcing them to find new paradigms of production in order to maintain their standing. It is not possible for traditional Italian medium-sized enterprises to compete with emerging countries in terms of production costs, but maintaining production inside the clusters assures the high manufacturing competencies that characterise Made in Italy. At the same time, goods manufactured in many developing countries are also increasing their quality despite offering low prices, leading industrial entrepreneurs to develop new paradigms of manufacture so producing items with added value; attracting customers by offering uniqueness. The concept of the “slow factory” is one of these new manufacturing approaches.

2 THE VALUE OF CRAFTSMANSHIP IN MANUFACTURING

2.1 Tradition and craftsmanship

Italian industrialization started in the postwar period thanks to small regional craft enterprises that based their production on local tradition and culture. Automation and mechanics industries have flourished in the Bologna area where silk mills have operated since the Middle Ages, the mechanical skills involved being transferred down through the generations. Glass manufacturing developed in Venice with the presence of craftsmen who produced objects for the courts of the richest and most powerful kings in XVI and XVII centuries and created a “glass culture” in this area. Tuscany leather garments and accessories are well known and in high

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

demand, with the territory holding a long tradition in this field thanks to the availability of raw materials and local skills. These are three examples of Italian clusters and many others could be mentioned. One of the points of strength of cluster enterprises is the capability of maintaining tradition and craftsmanship in production, creating a product that, despite being industrial, is still in some way unique.

Product value is mainly in intangibles like brand, style, and design and can reflect the culture of the area where the manufacture takes place. This issue is universal and can be applied to different regions of the world, not only in Italy, though perhaps it is in the Italian territory where the most significant application is found.

The industrial revolution enabled the production of high numbers of items by the use of machines. Mass production was achieved, allowing greater availability of goods for a larger number of customers. The diffusion and application of the Taylor theory to increase labour productivity contributed to the passage from craft to mass production, applying the principles of best practices, aiming to achieve maximum fragmentation to minimize skills requirement and job learning time. The manufacture of standardized products in huge volumes by unskilled workers using special purpose machines is the main issue of Fordism, a production principle born in the U.S.A. at the beginning of the XX century. It has been particularly popular in the automotive sector, though it is applicable in every kind of manufacturing process. Both Taylorism and Fordism present the idea of employing a work force that uses machines to do the job; workers who don’t need to actively participate in the manufacturing of the product, their actions being limited to the handling of machinery. Critics believe that this approach means operators are passive and not creative and this in turn causes a low quality of working life.

The Japanese answer to Fordism and Taylorism is Toyotism, a production management philosophy developed after the Second World War at Toyota by Taichi Ohno [1], a mechanical engineer who spent all his professional life at this enterprise. The Toyota Production System (TPS) was focused on reduction of the Toyota seven wastes “Muda” (Transportation; Inventory; Motion; Waiting; Over-processing; Over-production; Defects) through different tools and methodologies, such as “Just in Time” and “Kanban”, whose aims are the optimization of the production and the creation of product added value. The currently popular “Lean Manufacturing” approach can be considered an extension of Toyotism, where the capacity of the factory to quickly adapt to the market changes and customers needs has been enhanced. Lean manufacturing is primarily focused on designing a robust production operation that is responsive, flexible, predictable and consistent. This creates a manufacturing operation that is focused on continuous improvement through a self-directed work force and driven by output-based measures aligned with customer performance criteria. It develops a workforce with the capability to utilize the lean tools and techniques necessary to satisfy world-class expectations now and into the future [2]. The organizational aspect is therefore an important component of the lean factory, focusing on identification of people’s roles/functions, training in new ways of working, and communication. Workers are requested to be able to use the lean machinery and equipment, which largely involve electronics, therefore needing specialist skills, and to participate in the whole lean factory approach in terms of personal initiative and flexibility. Their role within the enterprise is more active than in a factory based on the Taylor or Ford approach, but still craft skills are not primary.

The idea of a revaluation of craftwork is not only Italian: some authors in recent years have enhanced this approach as a possible solution to the present economical crisis. Thomas L. Friedman [3] affirms "all that is standard is surpassed and American workers consider themselves as artisans in order to overcome the mass production paradigm and to make enterprises successful". Some “Makers” movements have recently come to life in the USA, with the underlying principle that people have an interest in making and repairing things. Richard Sennett [4] also believes that "our society needs to rediscover craft workers virtues, not with nostalgia for the ancient time but exalting the profile and characteristics of artisans (higher autonomy, dialogue with the client, social aspects of the job) in order to re-launch manufacture and create higher quality products". Chris Anderson [5], director of the magazine “Wired” maintains that "the next Industrial revolution will be led by a new generation of enterprises between high technology and craftwork, able to supply innovative products, highly personalized, on a small scale". In Italy a recent best-selling book by Stefano Micelli [6] discusses craftsmanship as the key word for a brilliant future for Made in Italy, describing how the history and tradition of handwork can still be the element to increase the competitiveness of Italian enterprises. Craftsmanship is described by Micelli as an “intimate familiarity and manual work on material and on shapes that it can assume”, something that the use of CAD doesn’t allow, where real images are created but devoid of concreteness. Francesco Morace and Giovanni Lanzone [7] talk about a “third Italian Renaissance”: after the first in XV century with figures such as Leonardo da Vinci and Michelangelo, the second in the 1950s with Italian design from the likes of Giò Ponti and Adriano Olivetti. This third Renaissance corresponds to a re-launch of Italian manufacturing, based on small and medium-sized enterprises, enhanced craftsmanship and strongly connected to the territory, local tradition and culture.

2.2 Sustainability and crafts-industrial production

The meaning of craftsmanship in manufacturing doesn’t refer only to the added value of the product in terms of quality and uniqueness but also to the sustainability of the manufacturing approach. Sustainable manufacturing implies methods and techniques of production that allow workers to express their skills and creativity, contributing to the improvement of the product and the competitiveness of the enterprise. Within a sustainable approach, workers can be craftsmen who are able to give to the product the added value that makes it unique and attractive to customers, and at the same time avoid frustration and boredom. Furthermore, the enhancement of craftsmanship in manufacturing often involves technologies that are sustainable so avoiding the type of mass production that generally utilises large amounts of raw materials and consistently produces waste; a mode of production that is not correctly balanced into the environment.

Another important issue is the ethics of production. Workers have to be treated well and justly, with company owners and managers being aware of their needs and rights. A crafts approach, enhancing the characteristics and skills of every worker, generally fits better with ethical practices, considering and respecting employee satisfaction.

Crafts-industrial production is therefore an interesting paradigm, one that allows the continuance of traditions and the culture of manufacturing activities as they were developed in previous times, but also embraces innovation in order to satisfy the new needs of the market.

3 SLOW FACTORIES

3.1 The slow factory

The term 'Slowness' can have a positive or a negative meaning. Dictionaries define 'slow' as "moving or operating at a low speed or not prompt to understand". Within the industrial realm slowness has always had a negative connotation, a slow production often meant higher costs and less profit, so the idea of slowness as a fundamental factor in the manufacturing of high quality industrial goods is rather new and unusual.

The original idea of **Slowness** is Italian. The first slow “concept” was Slow Food, founded in 1986 as Arcigola by Carlo Petrini in Torino. It started as a protest against the opening of a McDonald’s fast food restaurant in Piazza di Spagna in Rome and evolved into a movement against fast life; an attempt to recover good habits of eating and local food traditions. Since then many slow movements have been initiated: Slow Living [8]; Slow Economy [9]; CittàSlow; Slow Technology; etc.; but it's only recently that there has been talk of a Slow Factory.

The first attempt at defining a Slow Factory was made in 2012 by Enzo Baglieri, a professor at Bocconi University in Milano. His manifesto was published on a web blog and indicates three points that must be achieved by a factory in order to be considered “Slow”:

1. Awareness of the general context and scenario
2. To import intelligence and to export innovation
3. Responsible management, i.e., ethical practices and good treatment of the workforce.

These three points clearly refer also to sustainability, confirming the idea that the two concepts, sustainability and slowness, are strictly connected. The first point underlines the importance for a manufacturing activity to be integrated in the industrial, commercial and social system, taking into account the evolution of the market but also local culture and habits. Exchanges with other countries must be fostered in terms of importing human resources and export innovative technologies. The ethical issue in the management of a factory and of the labour force is fundamental. Managers must be aware of the workers' conditions and nurture a positive working climate in the plants. This manifesto represents a theoretical approach to the idea of slowness in manufacturing. It is possible to identify some practical applications in some enterprises located in Italy, whose production methods and technologies could suggest them as being examples of slow factories.

3.2 Cases

The current industrial system is generally based on highly automated manufacturing plants, which allow fast production and serial manufacturing. However, some Italian entrepreneurs, using their expertise and know-how, have decided to recover the value of tradition and craftwork and are finding that slow working processes can produce positive results and add a distinctive value to a product. A significant publication concerning the Italian manufacturing excellences identified as “art professions” is well described in a cultural study by Paolo Colombo [10]. In the following section, we will introduce four different cases where slow manufacturing is in parallel with industrial achievement.

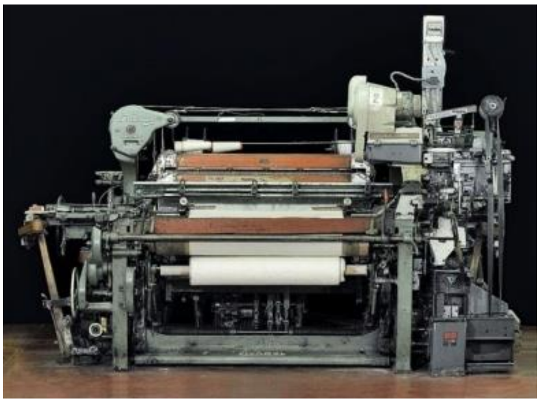


Figure 1: A full mechanical Japanese loom.

In the textile sector Giovanni Bonotto, an entrepreneur whose plants are located in an important industrial district in the north-east of Italy, has chosen to use, together with modern machinery, old Japanese looms which were built in 1957 and can produce high quality non-standardized fabrics (Fig. 1). Bonotto was the first to use the Italian expression “fabbrica lenta” that means “slow factory”. In his case, slowness is used in order to communicate a complex approach to textiles production: it corresponds to the use of completely mechanical machinery, eliminating the electronic element, and allowing the workers to act as craftsmen, for whom the loom acts as a tool to quicken the production and not as an automatic system that can substitute them. All weavers are skilled and the standard production that generally characterizes the textile industry is substituted by an industrial-artisan-craftsmanship that allows for the production of unique fabrics. One of the points of strength of a slow mechanical production is the possibility of using and mixing in the same fabric different materials such as cotton, wool, plastics and other fibres. Different threads are woven and compacted together, obtaining beautiful and non-standardized effects. New faster electronic technologies don’t give the same possibility of manufacturing as the old full mechanical loom provides. A vastly wide variety of thread materials can be chosen for their different characteristics such as thickness and robustness, and a high-density fabric can be realized; something not possible with an electronic machine, which would struggle with different materials and not be able to press the threads to the correct point.

Giovanni Bonotto controls all the production chain: paying particular attention to the creation of new fabric patterns, dying techniques and especially to raw materials. By testing innovative solutions, always enhancing the cultural heritage in the product and controlling the whole supply chain, the final possible imperfections of the fabrics - due to manual weaving or imperfections in the raw and natural materials - also become an unexpected point of attraction to customers. All this care and attention needs time and doesn't fit with the common standard methods of production. A phrase can represent the Bonotto company philosophy: "Time is the new luxury".

Pagani Automobili S.p.A. was founded by Horacio Pagani and proposes a number of versions of the Zonda model, a supercar designed in the '90s and realised using the most advanced technologies and materials but with the employment of exclusively artisanal skills in their workshop near Modena. Pagani came to Italy with a great passion for cars, having studied and gained a wealth of experience in Argentina. Following important collaborations with some of the most famous industries in Italy in the automotive field, he began the construction of his own product. Pagani's suppliers and partners are important industry brands, well known for their technological leadership. Recently, Pagani introduced its new project, the Huayra, which is considered today to be the fastest supercar. It is made of more than 4000 components, excluding the engine and the gearbox, and is designed, manufactured and assembled combining science, technology and art in a fully artisanal way.

The Pagani's design team develops the car design and skilled craftsmen manually assemble the thousands of components into the final product, without exploiting any of the automatic processes commonly used in car manufacturing plants. Despite new and advanced technologies and materials, manufacturing is still implemented as in a traditional Italian "bottega" (workshop and retail oulet).

Other significant examples of slow production are present in the Italian food sector. We have in particular examined some olive oil mills located close to Assisi, "Le Mandrie", and the medium-sized family enterprise "Babbi" which is near Cesena, accompany famous all over the world for wafers, sweets and creams. They both apply the concepts of slowness but in different ways. The idea is always to confer uniqueness to the product and to distinguish it from industrial and mass production.

Le Mandrie uses innovative machinery and equipment specifically designed with the most modern technologies to extract oil from olives (Fig. 2). The olive oil mills were designed and developed by the owners together with one of the most acknowledged producers of olive oil extraction plants, by exploiting specific knowledge gained from a long tradition in this field. In order to preserve nutritional content and maintain the special scent and flavour, it is necessary to avoid high temperatures during the chipping of the olives. For this reason, the mill works at a low speed with an enforced slowness that allows the highest quality olive oil to be obtained.

The core of the process was designed in order to achieve the best results from a natural high quality product cultivated in the hills near Assisi. The modern structure of the plant also allows for a more industrial production, using maximum capacity and velocity but, in this case, the final results will be different in taste and organoleptic effect. The main technical characteristic of the cold press extraction process for extra virgin oils, as realized in Le Mandrie shop, is that the extraction is based only on physical and mechanical principles. To cite some of the more peculiar aspects: the steel drums work slowly and the drupes together with the stones are divided into several parts; during this grinding process the produced fumes are suctioned; the following stage in the kneading machine is again slow because it doesn't use heat - which speeds up the process but reduces the flavour and nutritional content; during the extraction in the horizontal centrifuge or decanter a hot water process is avoided and only a small amount of cold water is added, thus maximising the organoleptic effect and preserving natural elements.

Figure 2: A modern innovative olive oil extraction plant.

A different idea of slowness is implemented at Babbi. In the production plant there is a mixture of old and modern machineries depending on the type of process. For example, candied figs, one of the Babbi's main products, need to be boiled for seven hours in a cauldron with a burner underneath (Fig. 3). The company has experimented with the process utilising new and modern machines already present and used for other purposes; in particular pasteurization was tested in order to increase production time and save money but the final product didn't taste the same. The old process is the only one that guarantees the uniqueness of this product.

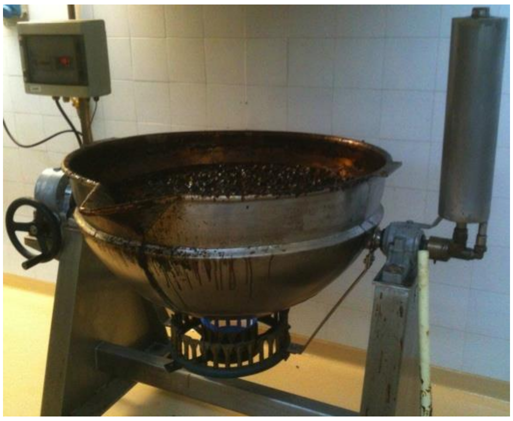


Figure 3: Cauldron for cooking candied figs.

3.3 Classification of slow manufacturing

The above-mentioned practical cases can generate a classification of slow manufacturing approaches that can be useful in understanding this phenomenon. Slowness can be implemented in different ways in terms of technologies and production machineries or methods of production. Depending on the kind of product and specific aims, different enterprises choose what is most suitable for them.

Machine/ Technology	Speed	*Notes*	*Industrial Reference*
OLD	**SLOW**	Old machines working at their fastest speed, considered slow by modern standards	Bonotto
NEW	**SLOW**	All the manufacture is manually made by skilled craftsmen	Pagani
NEW	**SLOW**	A slow speed is forced on modern machinery that could operate faster	Le Mandrie
OLD and NEW	**SLOW and FAST**	Both machinery and related speed are used depending on the products	Babbi

Table 1: Slow manufacturing classification

4 CONCLUSIONS

4.1 Present situation

A sustainable production means not only saving energy and reducing waste but also the quality of the workers' lives is important, along with the possibility for them to express their capabilities and skills. A recovery of tradition and old ways of manufacturing is therefore sought in order to improve work conditions but also to endow the product with an extra value that cannot be achieved through modern processes and technologies.

This is particularly true for food production, where only time-honoured methodologies can produce the desired results and taste, but is also relevant in other industrial sectors such as textiles.

The beneficial outcome of slow products has been confirmed with the general increase in the turnover of slow factories in recent years. The international success of “Eataly”, a Made in Italy foods distribution network, demonstrates that customers appreciate food and drinks manufactured in traditional slow ways and are prepared to pay a little extra for them, as long as their high quality is guaranteed.

A classification of these slow approaches has been made, identifying four ways of implementing slowness in manufacturing based on the choice of old or modern machinery and on the speed of production.

In present times, when the low costs of labour in developing countries has made it competitively difficult in Europe, some Italian entrepreneurs have adopted one or a combination of these approaches to offer a unique product and increase market shares.

4.2 Future developments

Further research is required in order to expand the analysis of slowness in manufacturing across a range of industrial fields and enterprises. Additional categories could be identified, denoting new and different approaches. The slow factory is still a new and challenging topic, particularly significant nowadays in the search to find new paradigms of production that assist industries in selling more and better products to a wider variety of customers.

The relations of the slow factory paradigm to sustainability are also significant and merit being deepened in technical and sociological terms.

5 ACKNOWLEDGMENTS

A special thanks to Prof. Raffaele Milani and the Laboratory for Research on the City of the University of Bologna.

6 REFERENCES

[1] Taiichi Ohno, 1988, Toyota Production System. Beyond large scale production, Productivity Press, New York.

[2] William M. Feld, 2000, Lean manufacturing. Tools, Techniques, and How to use them, CRC - The CRC Press Series on Resource Management.

[3] Thomas Friedman, 2012, Average is over, The New York Times, January 24 2012, A29.

[4] Richard Sennett, 2008, The Craftsman, New Heaven-London, Yale University Press.

[5] Chris Anderson, 2010, In the next industrial revolution, atoms are the new bits, Wired, January 2010.

[6] Stefano Micelli, 2011, Futuro Artigiano, Marsilio Editori.

[7] Francesco Morace, Giovanni Lanzone, 2010, Verità e Bellezza. Una scommessa per il futuro dell’Italia, Nomos Edizioni.

[8] Wendy Parkins, Geoffrey Craig, 2006, Slow Living, Berg Publishers.

[9] Federico Rampini, 2009, Slow Economy, Arnoldo Mondadori Editore.

[10] Paolo Colombo, Alberto Cavalli, Gioacchino Lanotte, 2009, Mestieri d’arte e Made in Italy, Marsilio Editore.

GCSM 11th Global Conference on Sustainable Manufacturing

2013
23rd - 25th September
Berlin - Germany

9.2 An optimization model for a sustainable agro-livestock industry

Nur Indrianti [1], Desi Perwati [2]

[1,2] Department of Industrial Engineering, Faculty of Industrial Technology

Universitas Pembangunan Nasional "Veteran" Yogyakarta

Jalan Babarsari 2, Tambakbayan, Yogyakarta 55281, Indonesia

[1] n.indrianti@upnyk.ac.id, [2] decy_milanisty@yahoo.co.id

Abstract

This paper deals with an optimization model for a sustainable agro-livestock industry. In this case, the agro industry established a subsidy program for the farmers in terms of utilizing pineapple skin waste generated from its production activities as the main cattle feed as a grass substitute. The policy is desired to increase welfare of farmers as well as minimize welfare deviation among farmers. The problem faced by the agro industry is to determine the cattle which will be fattened using the subsidized feed with regards to waste availability. The result of the study shows that the subsidy policy could improve welfare of the farmers and minimize welfare deviation among farmers. This indicates that such kind of subsidy policy can be use to promote sustainable development.

Keywords:

Agro-Livestock Industry, Optimization, Subsidy Policy, Sustainable Development

1 INTRODUCTION

Sustainable development has gained increasing awareness in recent years. The concept of sustainable development is widely used to assess the impacts of human activities on nature, environment, and resource base. The interdependent and mutually reinforcing pillars of sustainable development include economic development, social development, and environmental protection [1].

There have been literatures discussed about strategies to achieve the goal of sustainable development. On the manufacturing side, strategies have been developed to achieve sustainable manufacturing. One of the main focuses of sustainable manufacturing is showing a higher level of regard for the impact on the environment by minimizing water use, greenhouse gas emissions, waste generation, and energy requirements. In addition to protecting the environment, sustainable manufacturing further aims to improve the welfare of people, nature, and life in the future.

With regards to supply chain of manufacturing industries, the concept of sustainable manufacturing should be implemented along the supply chains. For example, a sustainable food manufacturing that uses agricultural material as an input should develop an approach which improves the economic, social, and environmental protection both for the manufacturing company and the agricultural industry as a supplier. On the downstream side, an industry should develop strategies that can reduce waste and pollution generated from distribution and after use activities. Thus, an integrated approach along the supply chain such as developing industrial park is necessary to develop to achieve the aim of sustainable manufacturing.

Government usually uses a range of policies to promote sustainable development. Literatures in economics provide extensive discussions and mentioned that economic instruments such as tax and subsidy provide one of the most effective public policy tools. The quality of life should be further increased by way of the environmental and economic benefits accruing from the implementation of the policy.

An integrated approach has been done by an agricultural industry called PT GGP. The company was established in 1979 in Lampung, South Sumatra, Indonesia and has evolved to be fully integrated pineapple plantation and processing facility to produce canned pineapple products and pineapple juice concentrate. PT GGP is now the third largest producer of canned pineapple products and pineapple juice concentrate in the world. The plantation currently consists of 33,000 hectares of land with production capacity of 500,000 tons of Cayenne pineapples annually [2]. In order to utilize pineapple skin waste produced by production activities, PT GGP established PT GGL as their subsidiary.

PT GGL is an agro industry in Terbanggi District, the province of Lampung, Indonesia. PT GGL is a company engaged in breeding cattle and began operations in 1987. The company utilizes PT GGP's pineapple skin waste as the main feed for cows as a grass substitute.

PT GGL has an area of 50 acres. Fifteen acres of the land is used for cowshed. In addition to breed local cattle, PT GGL imports Brahman Cross cattle types from Australia. PT GGL also processes pineapple peel, an abundant waste product that is difficult to dispose of, into pinemeal for internal use and for export to overseas markets, mainly Japan [3]

As an agro-based industry, besides having economic mission PT GGL has a social mission. This can be seen from the company's strategy in achieving its vision, such as establishing a close cooperation with the local communities in implementing community development.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

PT GGL has developed a partnership to more than 2,000 farms covering an area of plasma 6 districts with 48 villages in 17 districts. One of the types of the partnership is cooperation in cattle fattening. This partnership aims to provide knowledge and opportunity to the people to be able to maintain the cattle farming systems better than traditional systems, so that the income can be increased. This partnership will also facilitate the public in terms of feed that is in accordance to the standard owned by the company.

This study focuses on GGL's cooperation in cattle fattening, especially cow fattening. In this case, breeders or stock farmers prepare livestock production facilities such as bred cows and stables. The company gives subsidy to the farmers in terms of cattle feed with lower price than market price. At the end of the subsidy program, the farmers have to sell their subsidized cows to the company. The farmers do not pay the subsidized feed at the time they take the feed from the company, instead of paying the cost of the feed at the end of the program. So when the farmers sell the subsidized cows to the company, the farmers receive money from the company as the price of the cows minus cost of the subsidized feed. The feed has standard nutrition and cheaper than the normal market price.

The above description illustrates that PT GGL cares about the quality of life of surrounding communities. The company voluntarily operates subsidy policy without government intervention. This can be one example of industry's commitment to support the achievement of sustainable development. The social mission of PT GGL is intended to an increase in social welfare or poverty reduction, which is one of the challenges of sustainable development.

The utilization of pineapple skin waste for cattle feed is a practice of industrial ecosystem. The principle underlying 'industrial ecosystem' or 'industrial symbiosis' or 'eco-industrial parks' is that an industrial estate operates as an ecosystem, with wastes, by-products, production aids and energy being exchanged among closely situated firms [4 & 5].

The objective of this paper is to model the problem faced by PT GGL. The problem here is how to determine the optimal distribution of the subsidized waste cattle feed to the farmers with regards to waste availability and both for economic and social objectives of the company. We examine the model with a case study. It is then followed by a discussion about the benefit of a cooperation strategy as done by PT GGL to help promote the concept of sustainability.

There have been studies on the utilization of agro-waste. However, the studies concerned with different objects and objectives. A study on the optimization of the biogas yield from anaerobic co-digestion of manures and energy crops was done by Guilano *et al.* [6]. By applying the principles of Industrial Ecology and Ecological Modernization, Anh *et al*. [7] studied on the possibility and feasibility to develop an eco-agro industrial cluster including agriculture, fishery processing company, by-product pants, and waste water treatment units in Vietnam. Using dynamic model, Parsons *et al*. [8] developed an integrated crop-livestock model of farming practices exhibited in sheep system of Yucatan state. The study was to assess biophysical and economic consequences resulted by the interactions between farmer, crops, and livestock. Another study was done by Lin et al. [9]. The study aimed to propose a strategy for sustainable treatment of the livestock husbandry wastewater, which was to recycle anaerobic treatment effluent as irrigation water. It is clear that this study is different from previous studies.

2 SUSTAINABLE AGRO-LIVESTOCK INDUSTRY

Agro industry is an industry that adds value to agricultural products in the widest sense, including marine products, forest products, livestock, and fisheries [10]. Agro-industrial development will be very strategic when done in an integrated and sustainable. A synergistic and productive agro industry is one done by the application of agro-livestock industry [11]. Agro-livestock industry can be regarded as an attempt to integrate the agriculture and livestock industry. It is carried out in synergy where each business are integrated with each other "mutual support", "strengthening mutual" and "interdependence" by optimally making use of all potential resources owned by zero waste principle. There are some objectives of livestock integration such as to increase the use of local resources, resulting in zero waste and to improve the independence of the farmers [12].

Agro-livestock industry which is conducted through collaboration between the company and the surrounding community has the advantages for the farmers such as providing opportunity trying to farm livestock, additional revenues, ability to raise the technical and organizational, and togetherness among farmers and between farmers and companies. As for the company, such industry has the advantage of utilizing company's waste, increasing revenues from byproduct and marketing services livestock production, and a sense of belonging within the company [13].

3 A MODEL FOR SUSTAINABLE WASTE-BASED AGRO-LIVESTOCK INDUSTRY

The cooperation with stock farmers established by PT GGL described in Section one can be categorized as sustainable waste-based agro-livestock industry. In this case, the company try to optimally making use of pineapple waste to substitute main cattle feed resulting in zero waste. Moreover, in addition to reduce environmental impact, the program is desired to improve the welfare of the farmers.

The problem of the cooperation between PT GGL and stock farmers is illustrated in Figure 1. The figure shows that there are I farmers who want to participate in the subsidy program. Each farmer has g cattle that are categorized into local cow (l=1) and imported cow (l=2). The problem needs to be solved by the company is to decide which cow that will be subsidized in term of feed with special price (Cp_s). The objective of the subsidy program is to minimize the deviation of welfare among farmers (*DevH)* with regards to feed availability per period (A_t). When selling their subsidized cows, the farmers receive over the selling price of the cattle cut by the cost of the subsidized feed. The subsidy program is scheduled for fattening period of T. Unsubsidized cow is fattened with feed from outside the company with the price of Cp_b per kilogram, which is more expensive that the subsidized feed from the company.

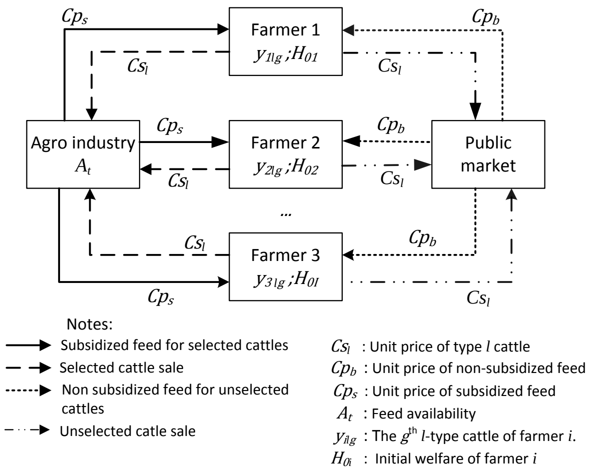


Figure 1: Sustainable agro-livestock industry

Welfare changes of farmer i during the subsidy period (σ_i) is represented by the difference between income (P_{Ti}) and family living cost of the farmer (D_{Ti}). The income can be from selling both subsidized and non subsidized cows and from outside livestock income. Thus, the welfare of each farmer at the end of the subsidy period (H_{Ti}) will be different. This difference is to be minimized by the company.

In developing the model of the case study, we used the following notations:

W_{0ilg}	:	Initial weight of the g^{th} type-l cow of farmer i at the end of the program (kg)
W_{Tilg}	:	The weight of the g^{th} type-l cow of farmer i at the end of the program (kg)
H_{0i}	:	Initial welfare of farmer i
H_{Ti}	:	Welfare of farmer i at the end of the program
P_{Ti}	:	Profit of farmer i at the end of the program
M_{Ti}	:	Total sales of farmer i at the end of the program
M_{0i}	:	Cows purchasing cost of farmer i
τ	:	A constant representing linearity of demand for cattle feed to cattle weight.
B_{Ti}	:	Total feed cost of farmer i at the end of the program
B_{Tsi}	:	Cost of subsidized feed of farmer i
B_{Tbi}	:	Cost of non-subsidized feed of farmer i
Q_{Ti}	:	Total demand for feed of farmer i for feed during the program
Cs_l	:	Unit price of type-l cow (Rp/kg)
Cp_s	:	Unit price of subsidized feed (Rp/kg)
Cp_b	:	Unit price of non-subsidized feed (Rp/kg)
Δw_l	:	The increase in weight of type-l cow (kg/day)
K	:	Number of days of the program (days)
k	:	The day of the subsidy period
t	:	Feed delivery period (t=1,2,…, T)
N	:	Number of days of feed delivery period (days)
n	:	The day of feed delivery
β_i	:	Net income of farmer i at the end of the program (Rp)
Δh_i	:	The changes of welfare index of farmer i
I	:	Number of farmers
A_t	:	Feed availability in each feed delivery period (kg)
D_{Ti}	:	Living cost of farmer i during fattening period (Rp)
y_{ilg}	:	Binary integer number, equal to 1 if the g^{th} type-l cow is selected for subsidy and 0 if otherwise
RT_i	:	Income outside cow fattening of farmer i

The model was developed based on the following conditions: (1) price of a cow is linear to his weight and the unit price is different for each type of cow; (2) feed price includes transportation costs; (3) welfare is linear to income and living cost; (4) cows are in a healthy or normal condition; (5) there is only a single market for cattle feed, so there is only one type of cattle price purchased from outside the company; (6) cow weight gained per day is constant and the same for the same type; and (7) subsidized feed meets the nutritional composition so that the changes in weight of the cow is assumed to be constant because the feeding is done on a regular basis.

The daily demand for cattle feed is linear to the weight of the cow. Based on the problem discussed earlier, the total requirement for feed of farmer i during the program can be formulated as follows:

$$Q_{Ti} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{l=1}^{2} y_{ilg}\, W_{0ilg} + \Delta w_l(k-1))\tau \quad (1)$$

$$\forall y_{ilg} = 1$$

Cattle feed requirement of each period is:

$$Q_{ti} = \sum_{n=1}^{N}\sum_{g=1}^{G}\sum_{l=1}^{l} y_{ilg}((W_{0ilg} + N\ (t-1)) + (n-1)\Delta w_l)\tau$$

$$\forall y_{ilg} = 1 \text{ and } t = 1, \dots, T \quad (2)$$

Total feed cost of farmer i is:

$$B_{Ti} = B_{Tsi} + B_{Tbi} \quad (3)$$

where:

$$B_{Tsi} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{l=1}^{2} y_{ilg}((W_{0ilg} + \Delta w_l(k-1)\tau)Cp_s \quad \forall y_{ilg} = 1$$

and

$$B_{Tbi} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{l=1}^{2} y_{ilg}((W_{0ilg} + \Delta w_l(k-1)\tau)Cp_b \quad \forall y_{ilg} = 0$$

Total cow purchasing cost of farmer i is a product of the initial weight of each cow and the unit price of cow, which depends on the type of cow:

$$M_{0i} = \sum_{l=1}^{2}\sum_{g=1}^{G} W_{0ilg}\ Cs_l \quad (4)$$

Final weight of the g^{th} type-l cow of farmer i can be calculated as follow:

$$W_{Tilg} = W_{0ilg} + (K-1)\Delta w_l \quad (5)$$

Total sales at the end of the fattening period of farmer i can be calculated as follows:

$$M_{Ti} = \sum_{l=1}^{2}\sum_{g=1}^{G} y_{ilg}\ (W_{Tilg}\ Cs_l)$$

$$M_{Ti} = \sum_{l=1}^{2}\sum_{g=1}^{G} y_{ilg}\ ((W_{0ilg} + (k-1)\Delta w_l)Cs_l) \quad (6)$$

Total profit of farmer i is derived from the total cattle sales at the end of the program minus total cow purchasing cost at the beginning of the period and the total feed cost during the program. Equation (7) describe the profit of farmer i.

$$P_{Ti} = M_{Ti} - M_{0i} - B_{Ti}$$

$$= \sum_{l=1}^{2}\sum_{g=1}^{G} y_{ilg}\ ((W_{0ilg} + (k-1)\Delta w_l)Cs_l - \sum_{l=1}^{2}\sum_{g=1}^{G} W_{0ilg}\ Cs_{l-}$$

$$(\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{l=1}^{2} y_{ilg}\ ((W_{0ilg} + \Delta w_l(k-1)\tau)Cp_s +$$

$$\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{l=1}^{2} y_{ilg}\ ((W_{0ilg} + \Delta w_l(k-1)\tau)Cpb) \quad (7)$$

Net income of farmer i is calculated based on his profit from the subsidy program and other incomes reduced by his family living cost during the program:

$$\beta_i = P_{Ti} + R_{Ti} - D_{Ti} \quad (8)$$

Assuming that the unit of welfare index is equal to Rp100,000,-, then the increase of the welfare of farmer i can be calculated as follows:

$$\Delta h_i = \frac{\beta_i}{100000} \quad (9)$$

Thus, the final welfare of farmer i is:

$$H_{Ti} = H_{0i} + \Delta h_i \quad (10)$$

The objective function, that is minimizing welfare deviation among farmers, can be formulated as follows:

$$Min\ DevH = \sqrt{\frac{\sum_{i=1}^{I}(H_{Ti}-\overline{H})^2}{I-1}}$$

$$= \sqrt{\frac{\sum_{i=1}^{I}((H_{0i}+\Delta h_i) - ((\overline{H_{0i}+\Delta h_i}))^2}{I-1}} \quad (11)$$

The constraints of feed availability can be written as follow:

$$\sum_{i=1}^{I} Q_{ti} \leq A_T$$

$$\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{g=1}^{G}\sum_{l=1}^{L} y_{ilg}((W_{0ilg} + N(t-1)) + (n-1)\,\Delta w_l)\,\tau \leq A_T$$

$$\forall y_{ilg} = 1 \text{ and } t = 1, \ldots, T \quad (12)$$

In addition to feed availability, the company determines minimum income from selling the subsidized cows (Equation (13)) and the minimum welfare to be achieved by each farmer (Equation (14).

$$\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{l=1}^{2} y_{ilg}\,((W_{0ilg} + \Delta w_l(k-1)\tau)Cp_s \geq 3000000$$

$$y_{ilg} = 0 \text{ or } 1, \text{for } \forall t \in T, i \in I, n \in N \quad (13)$$

$$H_{Ti} \geq 30 \quad (14)$$

4 NUMERICAL ILLUSTRATION

4.1 Case study

The model presented in the previous section was then examined using a case study where there are three farmers who follow the subsidy program. Table 1 show the farmers and their cows proposed for the subsidy program provided by PT GGL.

Table 1: Farmers and their proposed cows

i	H_{0i}	DT_i (x1,000)	RT_i (x1,000)	l	g	W_{0i}
1	20	Rp7,500,-	Rp7,000,-	1	1	250
					2	270
				2	1	300
2	27	Rp8,000,-	Rp7,000,-	1	1	200
					2	240
				2	1	220
3	15	Rp5.000,-	Rp5.000,-	1	1	280
				2	1	300

Subsidized feed composed of pineapple skin and concentrate with the ratio of 89%:11%. The unit price of subsidized feed is the sum of the price of pineapple skin of Rp100,- per kg and concentrate of Rp1,600,- per kg. Non-subsidized feed uses the same composition but different price of pineapple skin, that is Rp150,- per kg.

The local cattle that traditionally fattened will increase by an average weight of 0.5 kg per day. While the weight gain for the imported cattle is equal to 1 kg per day. If the cows are fed better than traditionally fattening the increased weight can be more than 0.5 kg per day for local cattle and more than 1 kg for imported cattle [14]. Weight changes in this study was 0.8 kg per day for local cow (Δw_1) and 1.3 kg per day for imported cow (Δw_2) as the feed has better nutrition, in which there is additional forage and concentrates which serves to add weight.

Other data are as follows:

Cs_1 = Rp23.000,-/kg	C_{Pb} = Rp400,-/kg	x = 7 days
Cs_2 = Rp22.000,-/kg	A = 2500 kgs	T = 16 weeks
C_{Ps} = Rp300,-/ kg	K = 100 days	

Based on Table1 and Equation (11) the objective function of the problem can be formulated as follows:

Minimize

$$DevH = \sqrt{\frac{\sum_{i=1}^{I}(H_{Ti}-\overline{H})^2}{I-1}} = \sqrt{\frac{\sum_{i=1}^{I}((H_{0i}+\Delta h_i)-(\overline{H_{0i}+\Delta h_i}))^2}{I-1}}$$

$$= \sqrt{\frac{((H_{01}+\Delta h_1)-(\overline{H_{01}+\Delta h_1}))^2 + ((H_{02}+\Delta h_2)-(\overline{H_{02}+\Delta h_2}))^2 + ((H_{03}+\Delta h_3)-(\overline{H_{03}+\Delta h_3}))^2}{I-1}}$$

$$= \sqrt{\frac{((20+\Delta h_1)-(\overline{20+\Delta h_1}))^2 + ((27+\Delta h_2)-(\overline{27+\Delta h_2}))^2 + ((15+\Delta h_3)-(\overline{15+\Delta h_3}))^2}{3-1}} \quad (15)$$

where:

$$\Delta h_i = \frac{P_{Ti} + R_{Ti} - D_{Ti}}{100000}$$

$$\Delta h_i = \frac{(M_{Ti} - M_{0i} - B_{Ti}) + R_{Ti} - D_{Ti}}{100000}$$

$$\Delta h_i = \frac{\left[\sum_{\ell=1}^{2}\sum_{g=1}^{G} y_{i\ell g}\left(\left(W_{0i\ell g} + (K-1)\Delta w_\ell\right) Cs_\ell\right) - \sum_{\ell=1}^{2}\sum_{g=1}^{G} W_{0i\ell g} Cs_\ell - \left\{\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{\ell=1}^{2} y_{i\ell g}\left(\left(W_{0i\ell g} + \Delta w_\ell(k-1)\right)\tau\right)C_{Ps} + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{\ell=1}^{2} y_{i\ell g}\left(\left(W_{0i\ell g} + \Delta w_\ell(k-1)\right)\tau\right)C_{Pb}\right\}\right] + R_{Ti} - D_{Ti}}{100000}$$

$$\Delta h_1 = 78.174y_{111} + 82.794y_{112} + 90.721y_{121} - 185.6$$

$$\Delta h_2 = 66.624y_{111} + 75.864y_{112} + 73.041y_{121} - 139.6$$

$$\Delta h_3 = 85.104y_{111} + 90.721y_{121} - 130.4$$

The Constraint of feed availability can be formulated as follows:

$$\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{g=1}^{G}\sum_{l=1}^{L} y_{ilg}((W_{0ilg} + N(t-1)) + (n-1)\,\Delta w_l)\,\tau \leq 2500$$

$$\boldsymbol{y_{ilg} = 0 \textbf{ or } 1, \textbf{for } \forall t \in T} \quad (16)$$

In addition to feed availability, the company has a target to achieve at least 30 of welfare for each farmer. It can be written as follows:

$$H_{Ti} \geq 30 \quad (17)$$

The company target on minimum farmer's income received from cow sales is described as follows:

$$\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{l=1}^{2} y_{ilg}\left((W_{0ilg}+\Delta w_l(k-1)\tau\right)Cp_s \geq 3000000 \quad (18)$$

4.2 Optimal solution

The problem was integer linear programming. We solved the problem with the help of LINGO software. The optimal solution can be seen in Table 2 to 5.

Table 2 Feed requirements for each cow in each period

Period (t)	Farmer 1 (kg)			Farmer 2 (kg)			Farmer 3 (kg)	
	S_{111}	S_{112}	S_{121}	S_{211}	S_{212}	S_{221}	S_{311}	S_{321}
1	176.68	190.68	212.73	141.68	169.68	156.73	197.68	212.73
2	181.58	195.58	217.63	146.58	174.58	161.63	202.58	217.63
3	186.48	200.48	222.53	151.48	179.48	166.53	207.48	222.53
4	191.38	205.38	227.43	156.38	184.38	171.43	212.38	227.43
5	196.28	210.28	232.33	161.28	189.28	176.33	217.28	232.33
6	201.18	215.18	237.23	166.18	194.18	181.23	222.18	237.23
7	206.08	220.08	242.13	171.08	199.08	186.13	227.08	242.13
8	210.98	224.98	248.43	175.98	203.98	192.43	231.98	248.43
9	215.88	229.88	251.93	180.88	208.88	195.93	236.88	251.93
10	220.78	234.78	256.83	185.78	213.78	200.83	241.78	256.83
11	225.68	239.68	261.73	190.68	218.68	205.73	246.68	261.73
12	230.58	244.58	266.63	195.58	223.58	210.63	251.58	266.63
13	235.48	249.48	271.53	200.48	228.48	215.53	256.48	271.53
14	240.38	254.38	276.43	205.38	233.38	220.43	261.38	276.43
15	245.28	259.28	281.33	210.28	238.28	225.33	266.28	281.33
16	250.18	264.18	286.23	215.18	243.18	230.23	271.18	286.23
Q_T	3414.88	3638.88	3993.08	2854.88	3302.88	3097.08	3750.88	3993.08

Table 3 Selected cows for subsidy program

Farmer (i)	Type (l)	Number (g)	Selected cow (y_{ilg})
1	1	1	
		2	y_{112}
	2	1	
2	1	1	
		2	
	2	1	
3	1	1	y_{311}
	2	1	y_{321}

Table 4 Cost components and income received by farmers

i	Initial capital (M_0), Rp	Total cost of feed (B_T), Rp	Income from cow sales (M_T), Rp	Profit (P_T), Rp
1	18,560,000,-	3,952,116,-	25,819,400,-	3,307,284,-
2	14,960,000,-	3,701,936,-	21,219,400,-	3,557,464,-
3	13,040,000,-	2,323,188,-	18,257,000,-	2,893,812,-

Table 5 Welfare changes during the program

Farmer (i)	Initial welfare (H_{0i})	Welfare changes (Δh_i)	Final welfare (H_{Ti})
1	20	28,07	48,07
2	27	25,57	52,57
3	15	28,93	43,94
	$DevH_0$ =6,03		$DevH_T$= 4,32

Table 3 shows that the optimal solution was selecting the second local cow of the first farmer (y_{112}), the first local cow of the third farmer (y_{311}), and the first imported cow of the third farmer (y_{321}). Based on the calculation result, there was no cow selected from the second farmer. In addition to feed availability, as indicated in Table 5, the welfare of the second farmer (27), which is better than the first farmer (20) and the third farmer (15), could be one reason that made the second farmer was not selected.

Table 5 shows that at the end of the program the welfare of all farmers increased. The level of the welfare was calculated based on the sale of both subsidized and non-subsidized cow, and the living costs of the farmer. This condition indicates that the company subsidy program could help farmers reduce feed costs and thus improve welfare as a result of greater income. The subsidy policy could also minimize welfare deviation among farmers, which was from

5 DISCUSSION

Table 2 shows feed requirements per period and total feed requirements until the end of the program for each cow. The table shows that feed requirements of each cow are different. This is because feed requirements depend on the weight of the cow. Feed requirements of each period will continue to increase along with the increasing weight of cattle.

6.03 to 4.35. This shows that such subsidy program could be used as a strategy to improve social welfare distribution. Table 5 also shows that although there was no cow selected from the second farmer for the subsidy program, the welfare of the second farmer increased relatively higher than other farmers. This suggests that in selecting the cow for the program, the company should pay attention on the income and living costs of the participated farmers.

6. SUMMARY

We have presented a model of sustainable agro-livestock industry. The problem discussed in the paper deals with a subsidy program established by an agro industry called PT GGL in which pineapple skin waste generated by the industry is utilized as the main cattle feed in cow fattening as a grass substitute. The subsidy program is desired to improve welfare of the stock farmers that the company in cooperation with as well as minimize welfare deviation among farmers.

The model presented in this paper discussed the optimization problem faced by the company. With regards to feed availability and the objective of the program, the company needs to select the cows proposed by the farmers.

The model was examined using a case study. The result of the study shows that the subsidy program could improve welfare of the farmers as well as minimize welfare deviation among farmers. This indicated that such a subsidy policy could be used as a strategy to promote sustainable development. This is because the policy could improve social welfare and income distribution while reducing company waste.

6 ACKNOWLEDGMENTS

The authors would like to thank Laila Nafisah from the Department of Industrial Engineering, Universitas Pembangunan Nasional “Veteran” Yogyakarta for her invaluable comments in this study.

7. REFERENCES

[1] World Commission on Environment and Development (WECD), 2002, The Johannesburg Declaration on Sustainable Development, World Summit on Sustainable Development (WSSD), http://www.johannesburgsummit.org/, accessed 24 August 2010.

[2] Gunung Sewu Group, 2013, Agribusiness: PT. Great Giant Pineapple, http://www.gunungsewu.com/ GGP. htm PT. Great Giant Pineapple, accessed 1 April 2013.

[3] Gunung Sewu Group, 2013, Agribusiness: PT. Great Giant Livestock, http://www.gunungsewu.com/ GGP. htm PT. Great Giant Pineapple, accessed 1 April 2013.

[4] Boyle, C.A. and Baetz, B.W., 1998, A Prototype Knowledge-Based Decision Support System for Industrial Waste Management Part I: the Decision Support System, *Waste Management,* Vol.18, pp.87-97.

[5] Ehrenfeld, J. and Gertler, N., 1997, Industrial Ecology in Practice: the Evolution of Interdependence at Kalundborg, *Journal of Industrial Ecology*, Vol.1, No.1, pp.67-79.

[6] A. Giuliano, A., Bolzonell, D., Pavan, P., Cavinato, C., and Cecchi, F., 2013, Co-Digestion of Livestock Effluents, Energy Crops and Agro-Waste: Feeding and Process Optimization in Mesophilic and Thermophilic Conditions, *Bioresource Technology*, Vol.128, pp.612–618.

[7] Anh, P.T., Dieu, T.T.M., Mol, A.P.J., Kroeze, C., and Bush, S.R., 2011, Towards Eco-Agro Industrial Clusters in Aquatic Production: the Case of Shrimp Processing Industry in Vietnam, *Journal of Cleaner Production,* Vol.19, Issues 17–18, pp.2107–2118.

[8] Parsons, D., Nicholson, C.F., Blake, R.W., Ketterings, Q.M., Ramírez-Aviles, L., Fox, D.G., Tedeschi, L.O., and Cherney, J.H., 2011, Development and Evaluation of an Integrated Simulation Model for Assessing Smallholder Crop–Livestock Production in Yucatán, Mexico, *Agricultural Systems*, Vol.104, Issue 1, pp.1–12.

[9] Liu, J., Wang, W., Zhang, Y., and Jiang, N., 2011, A Strategy for Sustainable Livestock Husbandry Wastewater Treatment in China, *International Journal of Environment and Pollution, Vol.45, No.1/2/3, pp.157-165*.

[10] Joewono, H.H., 2007, Agroindustry Marketing, http://www.alumni-tin.org, accessed 24 October 2010 (in Indonesia).

[11] Yudistira, Y., 2008, Potential Agro Industrial Employment, http://newspaper.pikiran-rakyat.com/, accessed 10 October 2009 (in Indonesia).

[12] Syukur, D.A., 2006, Optimization of Integrated Livestock through Third Party Networking Scheme, http://www.disnakkeswan-lampung.go.id, accessed 20 October 2009 (in Indonesia).

[13] Supriyati and Suryani, E., 2006, The Role, Opportunity, and Constraints to Develop Agro Industry in Indonesia, *Penelitian Agro Ekonomi*, Vol.24, No.2, pp.92-106, (in Indonesia).

[14] Munif, 2009, Change Hay to Beef, http://ternaksapiku.blogspot.com, accessed 3 December 2009 (in Indonesia).

9.3 Product carbon footprint in polymer processing – A practical application.

D. Khripko[1*], A. Schlüter[1,2], M. Rosano[3], J. Hesselbach[2]
[1] IdE Institute decentralised Energy Technologies gGmbH, Kassel, Germany
[2] Department for Sustainable Products and Processes (upp), University of Kassel, Germany
[3] Sustainable Engineering Group, Curtin University, Perth, Australia

Abstract
Light weight and synthetic polymer materials form the physical basis of many products across various applications worldwide. Given their reliance on fossil fuel inputs, this increases the importance of environmental assessment in the polymer industry. The energy intensity of plastics manufacturing and processing and the associated high embodied energy of polymer products warrants further investigation. The Carbon Footprint (CFP) methodology enables the estimation of the GHG emissions associated with polymer production. It quantifies the greenhouse gases released from polymer processing. An existing mid-sized polymer processing factory is utilised as a case study in this analysis. In addition, this study provides the data necessary for reviewing energy efficiency measures by estimating their value within CFP analysis. It also identifies the different strengths and weaknesses of the CFP approach. The analysis could then be used in plastics industry 'green' decision making.
Keywords:
Life Cycle Assessment; Energy Efficiency; Plastics Industry; Sustainable Manufacturing

1 INTRODUCTION

Climate change and the increasing production of greenhouse gases (GHG) is an important global issue. According to the IPCC, these emissions are largely caused by anthropogenic activities. The last validation of the goals of Kyoto Protocol highlighted that GHG concentration in the atmosphere is still increasing. [1]

The German Federal Ministry for Environment, Nature Conservation and Nuclear Safety estimated that the energy sector in Germany creates 40 % of the total emissions, followed by the manufacturing industry with 20 %, transport with 17 % and private households with 9 % [2]. As a result, today the major objective of GHG policies has centred on a reduction of emissions through increased energy efficiency. The quantification of industrial production on GHG emissions is important in determining the required environmental strategies.

A number of methods for environmental assessment of production activities exist. Some are focused on a specific industry or a product grouping, whilst others are more generally applied. In Europe the life cycle assessment based on ISO 14040:2006 is currently a very common approach in environmental impact analysis. Most evaluation instruments estimate a large number of assessed indicators. Different indicators and initial conditions make the comparability and the interpretation of the results inherently difficult. This type of data intensive assessment is especially difficult for small and medium-sized businesses and can be time-consuming and expensive.

2 METHODOLOGY

Carbon Footprint (CFP) is a method for the estimation of GHG emissions from both production and service industry activities. A CFP study should quantify the contribution of a product or service to climate change through global warming [3]. The assessment can cover the entire product/service life cycle [3]. The evaluated impact is described by a single indicator the 'CFP'. The CFP is measured through its Global Warming Potential (GWP) and is valued in carbon dioxide equivalent units [3]. The EN ISO 14050:2010 defines GWP as "a characterization factor describing the mass of carbon dioxide that has the same accumulated radiative forcing over a given period of time as one mass unit of a given greenhouse gas" [4]. The main greenhouse gases assessed include:

- Carbon dioxide,
- Methane,
- Sulphur hexafluoride,
- Nitrous oxide,
- Chlorofluorocarbons and
- Per fluorocarbons [5].

The CFP methodology is taken from the life cycle assessment approach [3]. Due to this the inventory and analysis process of the CFP conforms to the LCA principles [6].

3 STUDY DESIGN AND INVENTORY

The purpose of this study is the application of the CFP methodology in assessing polymer production for small and medium polymer processing companies. A medium size

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

polymer processing factory was used as a case study for the analysis.

Polymers are highly important manufacturing materials because of their light weight, heat resistance, high performance and extrudability characteristics. A common field for plastics is packaging [7]. In the sample factory different plastic lids are produced via injection moulding (predominantly packaging for food and tobacco products).

Injection moulding is a discontinuous process in the manufacturing of precast elements. The process begins with the heating and melting of polymer granulates. After that, the fluid polymer is injected into the mould´s cavity. Following the cooling down of the moulds they are opened. The lids are then released and packed.

The high variety of lids produced in the sample factory requires the selection of a few representative product types for assessment. Seven different products (lids) were estimated (Table 1). A single lid was defined as the functional unit. These lids have different weights; they are made out of various materials and fabricated on different machines. Additional selection factors were the annual manufacturing volume and the type of handling process.

Table 1: Assessed products (PP: polypropylene, PS: polystyrene, PE: polyethylene)

Lid	Material	Weight [g]
A	PP	5.5
B	PP	5.3
C	PS	16.0
D	PP	5.4
E	PE	9.3
F	PP	15.7
G	PP	15.3

Plastic lids are components of packaging and therefore an upstream product. Consequently the utilization phase and the end-of-life phase contribute significantly to the packaging life cycle. During assessment the system boundaries were restricted to cradle-to-gate in order to avoid the double counting of emissions.

The fabrication of plastic lids requires two separate inputs: the energy and material stream. The energy flows have been limited to electricity, cooling energy, compressed air, heating energy and warm water. The production process includes the different processes requiring chilling machines, compressors, fuel oil boilers, pumps and finished good storage.

In this specific product case study the number of material inputs is limited due to health and safety restrictions given by the food and tobacco industry. Only a few additives are allowed so that the main materials are polyethylene, polypropylene, polyester and dyes. Some of the lids contain paper or alumina gaskets. Apart from the materials involved in production, different packaging like cartons and plastic foil are also utilised.

During injection moulding, only marginal emissions are released to the environment. As a result, the output flows have been limited to scrap components and sprues. Therefore most of the plastic waste produced can be easily recycled. All energy and materials representing less than 5 % of the total flows were not included according to the cut-off boundaries in our assessment [8].

4 IMPACT ASSESSMENT AND ISSUES

Processing materials are usually audited through the internal purchasing systems, and the energy consumption is typically measured via energy meters. The CFP requires the calculation of material and energy flows to a single functional unit. Consequently, representative production lines and services need to be identified, measured and then converted into equivalent load units. Also the timing and duration of the necessary measurements requires planning. It is important to include start-up processes, mould changing time and associated machinery downtime within all processes.

4.1 Allocation of input and output flows

The indicated inputs and outputs are classified as both direct and indirect flows. For example, the energy consumption for the picking up and placing of lids is product-based and would not occur if there is no product to move. In contrast, the power consumption of pumps or general services does not relate directly to the processing system. Therefore, these are measurable only as a total amount. Given assessment norms, the case study applied the economic approach of cost accounting to the assessment of these indirect energy flows [9].

In economics, there are two basic cost-accounting approaches: marginal costing and full cost accounting. The classification of cost types and cost centres is common to both approaches. Full cost accounting is inward-looking. It is characterized by a focus on the product, and how much it costs to make it. Whereas marginal costing looks only at the additional cost of producing one more unit. [10]

Cost accounting differentiates between direct costs and general expenses. Direct costs can be completely attributed to the production of a specific good or service. General expenses are costs like administrative labour, energy, resources, etc. In marginal costing only direct costs are assigned to a product. [10]

Full cost accounting is the attribution of all costs to a production cost unit. The general costs are therefore allocated to a single product through the company-specific distribution criteria. This distribution is similar to the goal of a CFP study with the aim to assign all emission sources to a single product unit.

4.2 Classification of emission sources

The CFP assessment analyses the resultant emissions of a product or service and requires a definition of a functional unit (e.g: a single lid). The differentiation between direct emissions created by energy or by materials consumption is equivalent to the above definition of cost types. The allocation of emissions sources for each life-cycle phase can then be calculated (i.e.: emissions from the supply of goods, polymer production, emissions from the product fabrication processes and emissions in the usage phase, etc.).

Depending on the specific application, energy and material usage can be assigned directly to a specific product unit and was specified in Table 2 for the case study sample.

Whilst it is not always clear, if an energy flow is product-based, the assignment of materials by product category is apparent in most cases. The material compound data include the exact quantities required to produce one lid (the functional unit). All other materials and waste have been considered as indirect flows.

Table 2: Classification of measured flows

	Product-based	Indirect
	Energy	
Production	Power supply of machines Power supply of hot runners Compressed air demand of the mould Power and compressed air demand of handling systems	Power required for cooling energy generation Power for pumps, illumination, others
General services	None	Illumination Power demand of heating system pumps Other power
	Materials	
Production	Polymers Colour	Fuel Packaging Waste
General services	None	Fuel Waste

5 CFP RESULTS AND ANALYSIS

CFP calculation

The product-based flows were calculated from a production planning data base or were measured directly. Indirect energy and materials usage was calculated from the difference between bottom-up calculated annual product-based amounts and the total quantities consumed. For the assignment of these to a production unit two allocation possibilities exist: firstly the total number of units produced annually and the annual volume of polymers processed.

The allocation with the differentiation ratio “the total number of units produced” estimates an equal off-set of emissions to each lid (Equation 1). Whereas the second calculation approach “the annual volume of polymers processed” assigns the indirect emissions to 1 g of polymer. In the next step, these are multiplied with the lids weight (Equation 2).

Once the flow amounts are assessed the calculation of emissions produced is simple and requires the specific GWP values. The estimated amounts of the input and output flows are then multiplied by the GWP.

$$CFP = \sum_{i=1}^{n} CFP_i = \frac{1}{k_1} \cdot (m_1 \cdot GWP_1 + m_2 \cdot GWP_2 + \cdots + m_n \cdot GWP_n) \quad (1)$$

with:

i: number of the emission source 1 to n

m: total amount of an indirect flow

k_1: allocation factor – total number of units produced

$$CFP = \sum_{i=1}^{n} CFP_i = \frac{a}{k_2} \cdot (m_1 \cdot GWP_1 + m_2 \cdot GWP_2 + \cdots + m_n \cdot GWP_n) \quad (2)$$

with:

i: number of the emission sources 1 to n

m: total amount from an indirect flow

a: weight of a product unit

k_2: allocation factor – annual volume of polymers processed

The result of the calculation with the first differentiation ratio is 2.0 g CO_2e. The second approach considers the individual lid weight. Consequently, the indirect emission amount on the total CFP varies between 1.2 and 1.7 g CO_2e.

$$CFP = CFP_{direct} + CFP_{indirect} \quad (3)$$

The CFP is the sum of all direct and indirect emissions in the defined system boundaries under consideration of the chosen cut-off rules (Equation 3). The values estimated for the chosen lids are summarized in Figure 1. According to the given differentiation ratios, there are two scenarios for total CFP:

Scenario I: allocation of indirect emissions via the total number of units produced,

Scenario II: allocation of indirect emissions via the annual volume of total polymers processed.

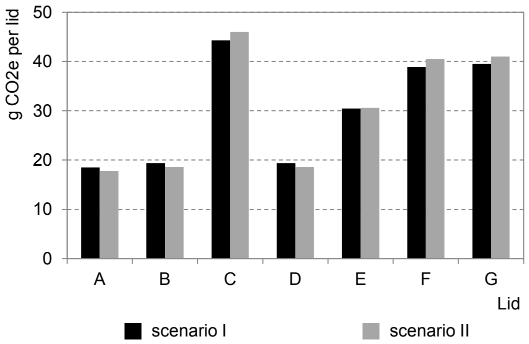


Figure 1: CFP of polymer lid (functional unit)

The estimated CFP values are between 18 and 44 g per unit. The total CFP of a lid varies between both scenarios by an average of 3.5 %. This gap depends on the indirect flow allocation coefficient utilised.

Analysis of the results

GHG emission reduction is a key factor in the context of both continuous improvement and efficiency management in polymer industries and within the broader corporate sustainability agenda. This analysis of the estimated CFP associated with the production of a polymer lid was aimed at the identification of potential measures to decrease the environmental impacts associated with various production inputs in polymer processing. As a result, the total CFP values were split into four categories:

- emissions created from product-based energy flows during production,

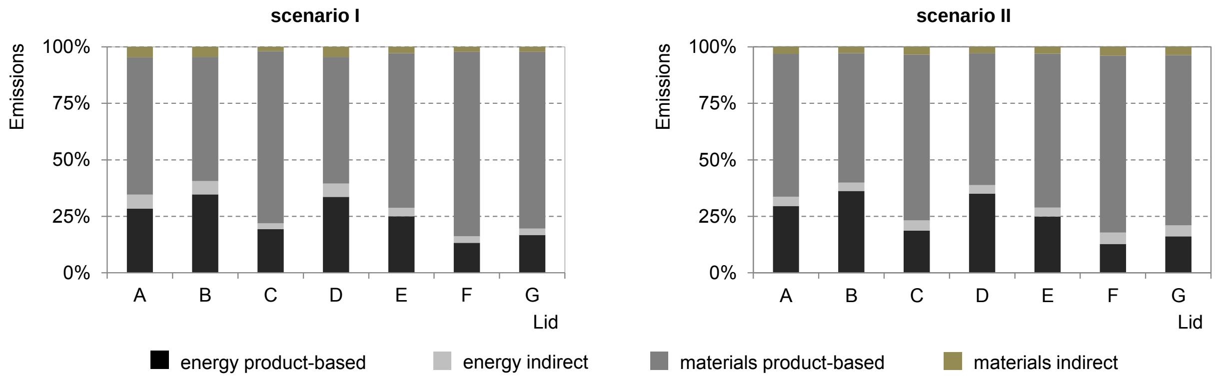


Figure 2: Emissions according to the flow type

- emissions created by indirect energy flows associated with production,
- emissions created from product-based material flows and
- emissions caused by indirect material flows.

The total emission amounts per production flow are shown in Figure 2. On average the indirect emissions were between 5 and 11 % of total emissions produced. Due to different general services the indirect emissions of energy are higher than those of the material inputs. The product-based emissions are up to 95 % of the total CFP and largely determine the total quantity of emissions. Overall more than 50 % of total CFP is attributed to materials. The GHG emissions of the materials are mainly released during the production and transportation stages. Consequently, the CFP is significantly determined by the emissions of the supply chain both prior to and after the processing stage.

Biopolymers are an alternative to conventional polymer plastics. Renewable materials are utilised in the production process and some are considered bio-degradable in the end-of-life waste stage. These new materials are currently commercially available but there are still a few challenges in their wider application. However, the physical properties of a biopolymer alternative do not always meet the high requirements of the packaging industry, particularly in the food industry. In addition, biopolymers are not always as suitable in many conventional plastics processing applications. The high costs of biopolymers are also a major limiting factor in current polymer processing technologies. [11]

A detailed examination of the emissions created during polymer processing is necessary in the identification of environmental improvement strategies for the polymer processing industry. As noted above, in this case study the emissions are largely created from the energy consumption associated with polymer production.

The comparison between total CFP and the lid's physical weight has indicated a positive correlation. This aspect was eliminated by normalizing the determined CFPs via the lid weight. In the Figure 3 the energy flows associated with lid production were further classified by the emissions associated with the moulding machines, hot runners and packaging (robot) systems.

Moulding machines in polymer processing consume the largest proportion of energy (including their control system, temperature aggregates, extruders and moulds) and are the main cause of CO_2e emissions in polymer processing. The physical ejection required from some moulds needs additional energy consumption in the form of compressed air. The company analysed in this research works with hydraulic machines and has also invested in the new hybrid machines. These include the advantages associated with hydraulic and electric drives which result in higher productivity and energy efficiency. The machines F and G are hybrid and the mentioned advantages were also confirmed by measurement. In the case of the purchasing of new assets an investment in hybrid moulding machines could also be recommended.

By implementing the above measures, plastics processing factories could decrease their total energy demand and reduce their GHG emissions. An additional solution is the substitution of the electric heating of the barrels with alternative energy sources. Although this process needs external thermal energy, the usage of electric energy is the standard practice. In most countries the primary energy factor

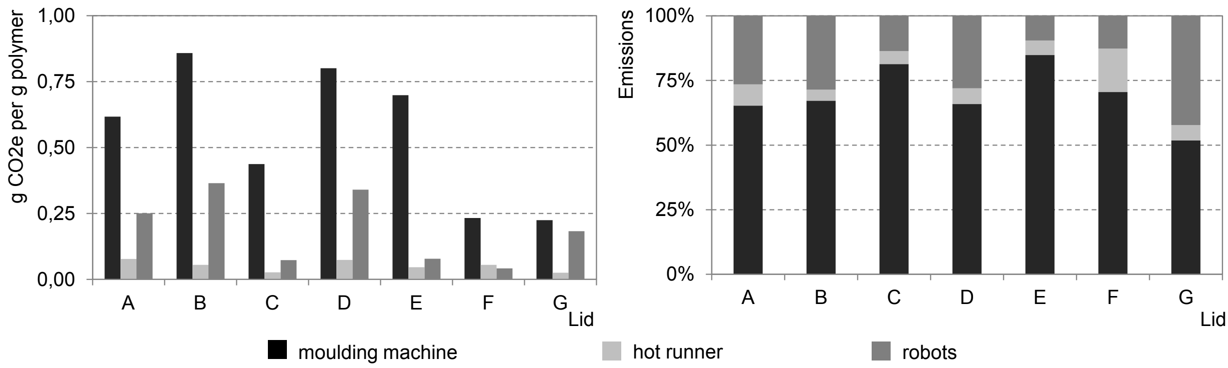


Figure 3: Normalised CFP

of electric power is very high. In Germany it is around 2.8 [12] due to the transmission and distribution losses (TND) in the transfer energy from electric power stations and the energy lost in conversion from heat (steam) to electric energy.

Decentralised energy generation can be one possibility for higher energy efficiency in various regions of the world (except for regions with high availability of wind or other renewable energy) [13]. The heat generated in combined heat and power plants (CHP) can also be used to supply the heating of the machines barrels. The linking with absorption chillers and other heating purposes enables the use of the rest of the available heat energy. The result is a higher utilisation factor. Additionally, emissions of the whole CHP system could be decreased through renewable fuels, like biogas or bio-methane.

The emissions associated with robotic packaging systems are largely created from electric power production and the generation of compressed air with its very high energy intensity factor (about 10 % of the compressor´s electric demand) [14]. According to own measurements, the substitution with electric alternatives could enable a saving of up to 70 %.

The above energy efficiency and co-generation options could certainly assist with the development of more eco-friendly plastics production.

6 CONCLUSION

This study has investigated the application of CFP in assessing the environmental footprint of polymer processing and production. Alternative cost management approaches were utilised in the analysis to provide a more objective assessment of the functional unit chosen. The various cost accounting methodologies available are assessed and compared to polymer production. This cost accounting assessment helps to clarify some of the difficulties that may be faced in estimating of CFP.

Reducing environmental impact assessment into one parameter/indicator is a challenge for any methodology. Other issues especially in comparison between different products are analogous to the challenges faced in life cycle assessment with different system boundary assumptions and different input and output data bases.

However, the CFP analysis provides an opportunity to develop an essential performance metric that can be used to improve sustainability management particularly in energy intensive industries. CFP can examine the value and importance of energy efficiency achieved in the product life cycle as well as in the important transition to renewable energy sources and materials/processes to reduce the overall carbon footprint.

In addition, packaging industries, whilst crucial in the transportation and storage of many products, often suffer from being over-engineered, with unnecessarily high material and energy intensity. CFP helps to highlight those areas of production that could benefit from further optimisation, in particular the potential reuse of the packaging to further enhance polymer industry sustainability.

Calculating and reducing the GHG emissions from polymer processing can also provide a significant competitive advantage for plastics companies for both economic growth and sustainable development.

Polymer processing relies on fossil fuel oil resources and high energy use in production both suggesting an inherent value from CFP analysis. The results in this research indicate that the key challenge for the plastics industry is in its ability to increase its level of energy efficiency whilst seeking alternative energy options.

7 ACKNOWLEDGMENTS

We thank the University of Kassel and the IdE Institute decentralised Energy Technologies gGmbH for their support. Furthermore, we thank to the G. Junghans Kunststoffwaren-Fabrik for their extraordinary cooperation.

8 REFERENCES

[1] Intergovernmental Panel on Climate Change (IPCC), 2012, Renewable Energy Sources and Climate Change Mitigation. Special Report of the Intergovernmental Panel on Climate Change, 7.

[2] Umweltbundesamt für Mensch und Umwelt, 2013, Nationaler Inventarbericht Zum Deutschen Treibhaus-gasinventar 1990–2011, 64.

[3] International Organisation for Standardisation, 2012, The Draft of the International Standard ISO/DIS 14067, Carbon footprint of products – Requirements and guidelines for quantification and communication, 13.

[4] DIN Deutsches Institut für Normung e.V., 2010, DIN EN ISO 14050:2010–08, Environmental management – Vocabulary (ISO 14050:2009), Trilingual version EN ISO 14050:2010, 69.

[5] International Organisation for Standardisation, 2012, The Draft of the International Standard ISO/DIS 14067, Carbon footprint of products – Requirements and guidelines for quantification and communication, 41–44.

[6] International Organisation for Standardization, 2012, The Draft of the International Standard ISO/DIS 14067, Carbon footprint of products – Requirements and guidelines for quantification and communication, 11.

[7] PlasticsEurope – Association of Plastics Manufacturers, 2012, Plastics – the Facts 2012 – An Analysis of European plastics production, demand and waste data for 2011, 7.

[8] DIN Deutsches Institut für Normung e.V., 2006, DIN EN ISO 14040:2006, Environmental management – Life cycle assessment – Principles and framework, German and English version (EN ISO 14040:2006), 24.

[9] International Organisation for Standardization, 2012, Draft Internation Standard ISO/DIS 14067, Carbon footprint of products – Requirements and guidelines for quantification and communication, 20.

[10] Götze, U., 2010, Kostenrechnung und Kostenmanagement, Springer-Verlag, 5, 153–154.

[11] European Bioplastics Organisation, 2011, Fact sheet – Better packaging with bioplastics, Information on technology and market development.

[12] Globales Emissions-Modell integrierter Systeme (Gemis), 2011, Ökoinstitut e. V. – Institut für angewandte Ökologie.

[13] Schlüter, A.; Rosano, M.; Böhm, S.; Calisir, N.; Hesselbach, J., 2012, Effects of Implementing Efficiency Techniques in the Plastics Industry in Germany and Western Australia – A Comparative Modelling Assessment. 10th Conference on Sustainable Manufacturing, conference proceedings, 525–530.

[14] Pohl, C.; Hesselbach, J., 2011, Substitution von Druckluft in der Produktion. Potentiale zur Senkung des Energiebedarfs, Industrie Management, 27/6, GITO Verlag, 21–24.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

9.4 Implementing energy efficiency in manufacturing – overcoming risk perception barriers and reducing cost impacts

N. Aughney [1], G. E. O'Donnell [2]

[1] Innovation for Irelands Energy Efficiency, Collinstown Industrial Estate, Leixlip, Country Kildare, Ireland.

[2] Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Ireland

Abstract

The increased complexity of manufacturing has resulted in process chains and equipment which demand more energy and resource categories. Energy management standards are being adopted by industries in order to focus on improving this capability; however there is recognition that a more detailed approach is required. This paper proposes a novel application of risk methods to energy efficiency projects by investigating the application of two structured problem solving techniques to energy efficiency improvements within complex manufacturing chains. The techniques evaluated were the 6-sigma and analytical hierarchy (AHP) processes. Industrial investigations and results to date indicate the benefit of utilizing such approaches. The approaches enable a structured method to engage the worker in assessing risk and highlight the value of minimizing risk to core Overall Equipment Effectiveness (OEE) metrics in order to ensure energy optimization opportunities can be implemented.

Keywords

Energy Efficiency, risk, structured problem solving

1 INTRODUCTION

An anticipated increase in Industrial energy demand across Europe will result in potentially a 30% increase in energy consumption over the next 20 years [1]. This will pose further challenges to Europe's commitment of reducing energy consumption by 20% by the year 2020 [2]. Energy efficiency as a result is becoming a key topic within industrial environments as a response mechanism to this challenge. This is broadly being addressed by three different approaches within industry; engagement with management in terms of leadership, energy efficiency technology implementation and adherence to policies/regulations [3]. Historically facilities management and technical building services have championed energy efficiency improvements. Improving data availability and knowledge of manufacturing processes have been highlighted as challenges to the implementation of further sustainable practices [4]. The increased complexity of manufacturing equipment and process chains is resulting in increased demands for both energy and resource categories [5]. This is presenting a further challenge to energy efficiency improvements within industry due to the heavily compliant nature of these environments.

The adoption of energy management standards by industry, most notably the ISO50001 standard [6] is seen as an avenue to address this deficiency through the development of organization capability. Although this standard does place a heavy emphasis on monitoring and metering there is no formal risk consideration to the standard. The development of more detailed approaches is ongoing; ISO50004 through the ISO T/C242 and the SEAI [7, 8], is being pursued as well as improvements in energy awareness and consumption prediction models of production systems [9].

Risk assessment does form an integral part of decision making within many industries and disciplines. This is reflected through the design of machines or systems [10], identifying key factors in supply chain risk [11] and risk to project schedules [12]. Its primary role being to identify key factors that can impact core operating capabilities [13] to allow mitigation actions to be identified.

From a manufacturing perspective, engagement with appropriate experience within a workforce can support the identification of these factors. The application of lean techniques such as kaizen [14] and process mapping [15] utilise this experience. This suggests leveraging appropriate knowledge in a structured way to evaluate improvements has potential and has the additional benefit of identifying success criteria to support future risk mitigation [16] of core OEE metrics. Early work in applying this approach to energy efficiency within factories has been demonstrated [17]. This has the potential of delivering significant initial energy savings with minimal capital expenditure [18]. A formal path to assessing benefits, opportunities, costs and the risks associated with proposed solutions is the Analytical Hierarchy Process [19] where a problem is structured as a hierarchy through criteria and alternatives. Proposed alternatives can be evaluated in terms of defined and weighted criteria to ensure appropriate relevance to an overall problem statement [20]. The criteria defined; through the weighting process can ensure the appropriate dominance of customer needs [21]. This paper provides an overview of how workforce engagement, with appropriate consideration of risk factors can deliver energy efficiencies within compliant environments.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

2 INDUSTRIAL ENVIRONMENT

Energy consumption within industrial settings is a consequence of operations and manufacturing activity. As a result there is a direct relationship between waste within manufacturing process chains and energy inefficiencies, as shown in figure 1. This does however allow factories at an early stage in an energy improvement plan to improve energy efficiency through operational focus.

Waste Type	Energy Use
Overproduction	More energy consumed in operating equipment to make unnecessary products
Inventory	More energy used to heat, cool and light inventory storage and wharehousing space
Transportation and Motion	More energy used for transport
Defects	Energy consumed in making defective products
Over Processing	More energy consumed in operating equipment related to unnecessary processing
Waiting	Wasted energy from heating, cooling and lighting during production down time

Figure 1: Manufacturing and energy waste [13]

The complexity of manufacturing process chains and how they reside within their factory environments can create challenges. Specifically when considering unit or sub unit processes from both an energy and resource point of view. It can be seen from figure 2 that there are many inputs into a system which can require characterization initially. This is necessary to ensure appropriate performance information is understood for baseline performance referencing but also to ensure boundaries are well defined. For example, what resource category is included and which sub unit will be characterized for improvement. This discipline is critical to supporting the identification of risk factors and potential mitigation plans.

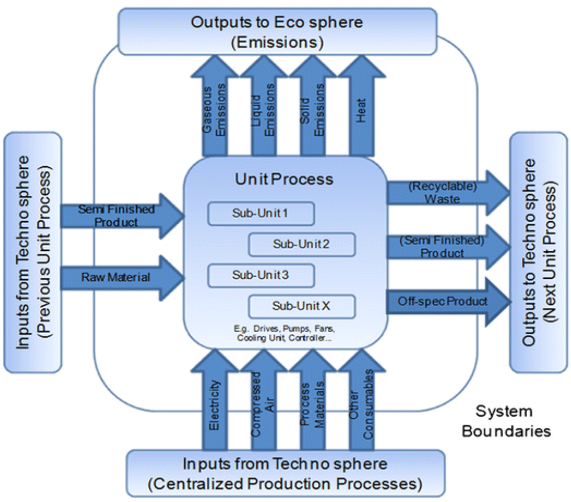


Figure 2: System boundaries and complexities [22]

3 RISK EVALUATION: FUNCTIONALITY

By engaging the appropriate workforce in brainstorming energy improvements on targeted production systems, their unique perspective on opportunity and their familiarization of process chains through preventative maintenance and good manufacturing practices can be leveraged. This level of experience in performing equipment based tasks ensures a thorough knowledge of what targeted equipment is functionally capable of. Manufacturing process equipment is historically optimized for functionality in terms of output and repeatability. As a result, optimised energy performance can be overlooked as a core requirement in production system set up. In terms of comprehending how capable targeted production equipment is of being optimised with respect to energy consumption, a number of considerations must be understood for example; safety, availability, quality and cost implications. By evaluating improvements in terms of tool ability or functionality, it allows an early opportunity for mitigation plans to be identified to allow energy optimizations, as shown in figure 3. This process will validate some opportunities as being feasible and potentially eliminate or delay some opportunities. Delays can be due to potential upgrades or improvements being required to support the energy improvement opportunity which may require capital funding.

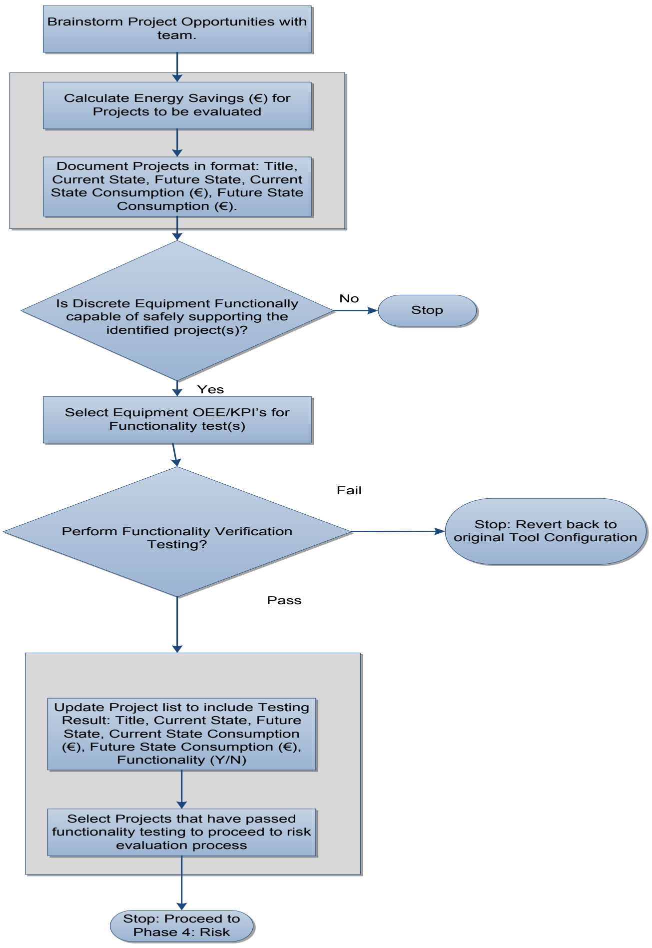


Figure 3: Top level approach to evaluating functionality

4 RISK EVALUATION: OEE

In terms of production systems, risk needs to be considered with respect to production impacts, in particular when one-of-a-kind production tools are present. To develop a deeper understanding of risk factors, functionally valid opportunities should be considered in terms of OEE and process chain performance. This can be achieved by targeting appropriate factory metrics (KPI's) which production equipment is managed to within a factory environment, for example availability or up time (A_1), quality or percentage of material within defined customer criteria (A_2) and cost of ownership of production equipment (A_3). Factory databases are used to collect this KPI information. A normalized or set of prioritization values B_1, B_2, B_3 can be generated, as shown in equation 1, which reflects how equipment performance is prioritised by resources on a shift level, daily or weekly basis. Within factory work cells or process chains, performance requirements are well understood but an understanding in terms of hierarchy can often be missing; this approach can facilitate this understanding and allow the appropriate KPI's to be targeted for more detailed further analysis.

$$\begin{array}{c c} & \begin{array}{cccc} \boldsymbol{A_1} & \boldsymbol{A_2} & \boldsymbol{A_3} & \textbf{Priorities} \end{array} \\ \begin{array}{c} \boldsymbol{A_1} \\ \boldsymbol{A_2} \\ \boldsymbol{A_3} \end{array} & \begin{bmatrix} 1 & a_{12} & a_{13} \\ 1/a_{12} & 1 & a_{23} \\ 1/a_{13} & 1/a_{23} & 1 \end{bmatrix} \begin{array}{c} B_1 \\ =B_2 \\ B_3 \end{array} \end{array} \qquad (1)$$

As factory's are dynamic environments with multiple parameters or KPI's being managed, this subsequent testing provides the chance to ensure any potential gaps in the initial functionality testing that may only become apparent over time are noted. In order that no opportunities are rejected early this will allow potential improvement or mitigation steps to be actioned early to ensure no opportunities are rejected incorrectly. It also allows personnel from outside the production environment to understand what KPI's need to be evaluated in any projects that may impact production line performance. Figure 4 highlights a flow to evaluate how to identify effective KPI monitoring post functionality testing.

Within each of these performance metrics A_1, A_2 and A_3, how these metrics monitor performance, what reason they were put in place and their capability to support the management of a production line can also vary depending on the requirements at time of creation. As a result, it is necessary to formally understand what value the individual performance metrics deliver in terms of the manufacturing process chain, how and why they are used. This will ensure tailored monitoring can be defined to gain the maximum level of information when evaluating energy improvements. This can be achieved by reviewing each KPI in terms of the following capabilities; Likelihood (*L*), Detectability (*D*) and Severity (*S*). Where likelihood is defined in terms of the possibility of an energy change impacting a KPI, detectability is defined in terms of the ability of a KPI to detect a change and severity is defined as the negative impact of the change.

An importance value (*I*) can be assigned to each KPI in terms of L, D and S. For example the importance value (*I*) assigned by the workforce to the possibility of detecting a change (*L*) to the availability metric (A_1) is denoted as; I^L_{A1}

This will allow the workforce to weight the ability of the individual performance metrics to manage energy based change. Projects identified for example, Z_1 and Z_2 can be assigned by the workforce based on their experience, to the possibility a change in performance of a KPI (A_1, A_2, A_3) in terms of Likelihood (*I*), Detectability (*D*) and Severity (*S*). For example a Likelihood value (*L*) can be assigned by the workforce to the possibility of observing a change in the availability metric (A_1) if project Z_1 was implemented can be denoted as; L^{Z1}_{A1}

Likelihood (*I*) and Severity (*S*) are only considered for Availability (A_1) and Cost (A_3) as these metrics are extensively tracked within production environments which results in effective monitoring. Due to the high degree of variability that can occur in terms of Quality (A_2), detectability (*D*) should be considered.

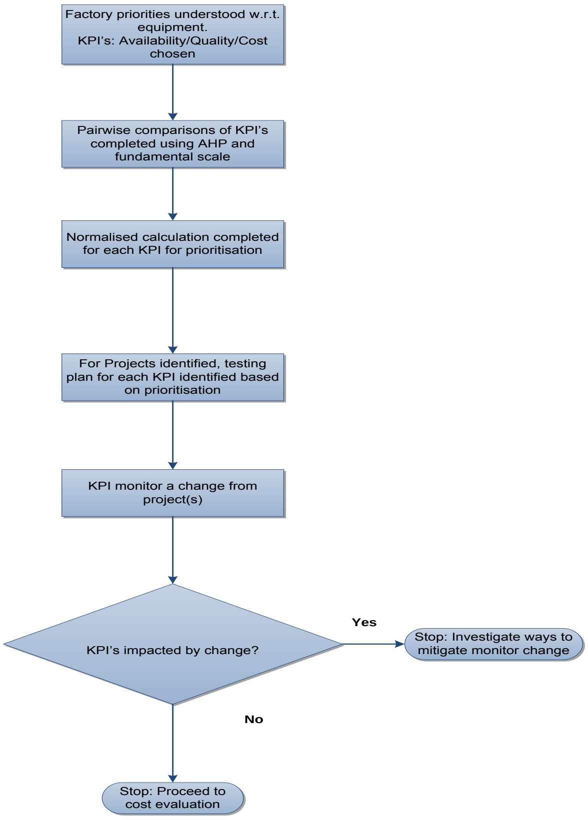


Figure 4 – Decision chart for OEE evaluation

The scoring values assigned reflect the workforces view on changes occurring to the KPI's in terms of Likelihood (*L*), Detectability (*D*) and Severity (*S*) as a result of energy projects, for example Z_1 and Z_2 being implemented. A capability score can then be calculated, as shown in equation 2 for project Z_1 which reflects a factory's ability to monitor and manage a change based on a company's priorities and capabilities.

$$Z_1 = \begin{bmatrix} B1\left((L^{Z1}_{A1} \times I^L_{A1}) + (S^{Z1}_{A1} \times I^S_{A1})\right) + \\ B2\left((L^{Z1}_{A2} \times I^L_{A2}) + (D^{Z1}_{A2} \times I^D_{A2}) + (S^{Z1}_{A2} \times I^S_{A2})\right) + \\ B3\left((L^{Z1}_{A3} \times I^L_{A3}) + (S^{Z1}_{A3} \times I^S_{A3})\right) \end{bmatrix} \qquad (2)$$

6 CASE STUDY

An industrial boilerclave system, as shown in figure 5 was targeted to identify an optimized idle consumption state within a medical device manufacturing facility. The function of the system is to remove wax from a ceramic mold, with steam at operating temperatures between 160-180ºC. It is a process involving condensation, conduction and flow through a porous media. The main energy driver is electrical energy which is used through heating elements to create saturated steam. The process involves saturated steam (liquid & vapour), solid and liquid wax, wet and dry porous ceramic shells and air. The system is a one of a kind tool and as a result the production environment is sensitive to potential production impacts.

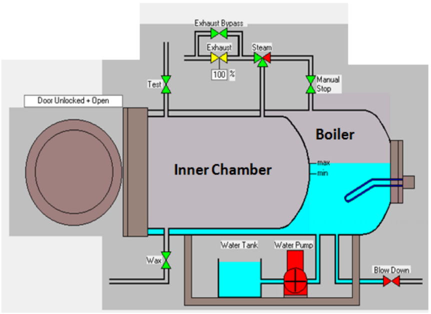


Figure 5 – Boilerclave system

From initial investigations in earlier work, 2 opportunities were identified as potential candidates for subsequent evaluation [23], as shown in table 1. Both settings met the initial concerns regarding functionality and were considered for evaluation in terms of OEE metrics.

Experiment	Pressure setting (psi)	Mean Power (kW)	Recovery Time
Reference	136	27	0
Exp #1 (Z_1)	100	14	6 mins
Exp #2 (Z_2)	80	7	12 mins 47 secs

Table 1 – Experimental summary

The KPI's; availability, quality and cost (A_1, A_2, A_3) were identified through a survey of the work cell as the critical parameters which the workforce focuses on with respect to the boiler cleave system. Table 2 reflects how the workforce prioritised these KPI's with respect to each other. This indicated experiment #1 (Z_1) being considered for further evaluation.

KPI	A_1	A_2	A_3	Priority
A_1	1	7	9	70%
A_2	0.14	1	5	25%
A_3	0.11	0.2	1	5%

Table 2 – Work cell priority

Table 2 reflects the significance of availability in the prioritization analysis indicating that 70% of area resource time focuses on maintaining availability performance. This resulted in a scoring matrix which reflected the workforces view on changes occurring to the KPI's, as shown in table 3. A simple scoring mechanism (1=bad, 10=good) was used to capture the workforces data based viewpoint.

KPI	Project	L	D	S
A_1	Z_1	8		8
	Z_2	3		3
A_2	Z_1	8	8	8
	Z_2	8	8	8
A_3	Z_1	9		9
	Z_2	9		9

Table 3 – Workforce input on ability on monitor energy projects

Using equation (2), each project was then scored, as shown in table 4. The value outlines the capability of the factory to monitor each project appropriately, rather than just a success rate.

Project	Capability
Z_1	8.1
Z_2	4.6

Table 4 – Project capability scores

This analysis improved confidence in identifying what upgrades would realize the energy savings estimated from the characterization completed. The relative difference within the scores highlights, based on the collective experience of the workforce used, gaps in a factory's capability to manage a change. In terms of projects identified, the relative difference in scoring is attributed to the impact on the availability KPI. This analysis improved confidence in identifying what upgrades would realise the energy savings estimated. The options selected were an upgrade to the human machine interact (1) and a modification to the systems PLC control (2) as shown in table 5. Both options were deemed suitable to factory management as a result of the process used with option 2 ultimately being selected on a cost basis as risk considerations were deemed to have been comprehended.

Option	Upgrade Considerations	Install Price (€)
1	HMI Upgrade	10,000
2	Switch Installation	5,000

Table 5 - Upgrades

A separate study was completed on all known equipment failure mechanisms to evaluate upgrades identified. A 6-sigma FMEA template approach was used which leveraged workforce and vendor experience to identify concerns, as shown in table 6. These involved analyzing historical failures to ensure all known failure mechanisms were comprehended prior to testing design. This allowed factory maintenance databases and vendor input to support the evaluation of each concern to ensure an accurate quantification.

Tool Subcomponent/Behavior Change	Concern	Evaluation	Risk Impact (1-10)	Probability of Impact (0-1.0)	Risk Measurement	Risk (H/M/L)
5X24 kW elements	Contactor Frequency Change	Lowered Pressure setting to 100psi to reduce the contactor frequency to the elements. Note: Elements are RTF.	1	0.1	0.1	L
5X24 kW elements	Ramp Frequency	Changing ramp frequency of current on the contactors/elements	1	0.3	0.3	L
100 psi setting	Issue with contactor	New change will have less contact between the contactor and element, will extend life of contactor as it is currently 'run to	3	0.1	0.3	L
Ramp frequency of contactors	Contactor operational profile changes	6 min recovery monitored during testing, no issues noted on tool during tests, no impact	2	0.1	0.2	L
Tool may not go from 100 to 136 psi when requested	This will be tested during tool upgrade by LBBC.	Upgrade designed to avoid this	2	0.1	0.2	L
Wax won't melt due to	Tool will only run at 136 psi	To be verified during LBBC	2	0.1	0.2	L
Door opens at 100psi	Misprocess	Door interlock requested for upgrade to ensure this does not	3	0.1	0.3	L
Door won't open at 136 psi	Normal risk	No different to current tool setting	1	0.1	0.1	L
Change does not work	If change does not work it will be reversed.	All exps completed to date prove the change will work. No impact to product as 136psi is maintained	3	0.1	0.3	L
PLC change causes machine to behave	To be fully tested with LBBC during upgrade.	To be verified during LBBC upgrade	2	0.1	0.2	L
New operational sequence for associates	GMP and ECC documents to be modified.	To be verified during LBBC upgrade	1	0.2	0.2	L
Safety implications with change	Change will not exceed 136psi as per current setting. . The tool will be operating at an average lower pressure with the change. No change to outer chamber - it will see 136 operational	Change has been manually tested multiple times	3	0.1	0.3	L

Figure 6 – FMEA Output

7 SUMMARY

The study outlined in this paper highlights the importance of considering risk factors to minimise subsequent cost impacts to ensure successful energy based project selection due to potential impacts on production environments. The approach outlined helps to address perceptions and concerns that arise within industrial environments due to project implementation. The potential impacts documented include both tool performance and production line performance. Workforce engagement in understanding both of these considerations was crucial. Using structured problem solving techniques ensured an effective capturing of workforce knowledge in terms of equipment functionality and OEE impacts. To support this understanding the 6-sigma FMEA structure proved effective at capturing workforce experience in identifying potential failure mechanisms which may impact project implementation. The analytical hierarchy proved effective at ensuring an accurate picture of work cell priorities were understood which allowed critical OEE metrics to be prioritised and monitored to ensure compliance. The structure outlined provided confidence to factory management that workforce experience identified appropriate solutions with minimal risk. The solutions outlined also displayed significant savings over a 5 year period, with Z_1 yielding €58,000 and Z_2 €88,000 savings over the period outlined. This highlighted the cost positive impact of energy based projects that can be achieved within manufacturing process chains.

8 ACKNOWLEDGMENTS

We extend our sincere thanks to all who supported the results outlined in the paper. Most notably we would like to acknowledge the support given by Mr. Barry Kennedy, the C.E.O. of the Innovation for Irelands Energy Efficiency consortium. Finally the authors would like to recognise the support given by Enterprise Ireland and the Industrial Development Authority of Ireland to this work.

9 REFERENCES

[1] Report by the EU Director General for Energy, 2009. "EU Energy Trends for 2030".

[2] EU Director General for Energy, 2011. "Energy Efficiency Plan 2011". Accessed on 6 February 2013.
http://ec.europa.eu/energy/efficiency/eed/eed_en.htm

[3] Abdelaziz, E., Saidur, R., Mekhilef, S., 2011. "A review on energy saving strategies in industrial sector". Renewable and Sustainable Energy Reviews 15:150-168.

[4] Elmualim, A., Shockley, D., Ludlow, G., Shah, S., 2010. "Barriers and commitment of facilities management profession to the sustainability agenda" Building and environment 45:58-64.

[5] Gutowski, T., Murphy, C., Allen, D., Bauer, D., Bras, B., Piwonka, T., Sheng, P., Sutherland, J., Thurston, D., Wolff, E., 2005, Environmentally Benign Manufacturing: Observations from Japan, Europe and the United States, 13/1: 1-17.

[6] International Organisation for Standardisation, 2011, ISO50001, WWW.ISO.ORG.

[7] Report by the Sustainable Energy Authority of Ireland, 2010,ISO50004, http://www.seai.ie/Your_Business/Large_Energy_Users/LIEN/LIEN_Reports/LIEN_Annual_Report_2010.pdf

[8] International Organisation for Standardisation T/C 242, 2012, ISO50004.Accessed on 1 March 2013.
www.iso.org/iso/home/store/catalogue_tc/catalogue_tc_browse.htm?commid=558632

[9] Quilligan, F., Upton, C., "Visual decision support for energy aware manufacturing", *Proceedings of the 10th global conference on sustainable manufacturing (CIRP)*, pp453-458.

[10] Klein, J., Cork, R., 1998, "An approach to technical risk assessment", International journal of project management, 16/6: 345-351

[11] Li, X., Xie, Q., 2009, "A method of identifying supply chain risk factors", IEEE World congress on software engineering, pp369-373

[12] Project Management Institute, 2004, PMBOK Guide, pp249-257.

[13] Silvestri, A., Cagnoa, E., Trucco, P., 2009, "On the anatomy of operational risk", International conference on industrial engineering and engineering management, pp2174-2179

[14] United States Environmental Protection Agency, 2011, "Lean Manufacturing and the Environment". Accessed on 10 March 2013.
http://www.epa.gov/lean/environment/toolkits/environment/index.htm

[15] Sustainable Energy Authority of Ireland, 2009, "Alternative Methodologies". Accessed on 12 March 2013.
http://www.seai.ie/Your_Business/Energy_Agreements/Special_Working_Groups/AM_SWG_2008/AM_Project_Report.pdf

[16] Cagno, E., Worrel, E., Trianni, A., Pugliese, G., 2012, "Dealing with barriers to industrial energy efficiency: an innovative taxonomy". European council for an energy efficient economy, 759-707.

[17] Karnouskos, S., Colombo, W., Lastra, M., Popescu, C., 2009, "Towards the energy efficient factory", 7th IEEE International Conference on Industrial Informatics.

[18] Gonce, A., Somers, K., 2010, Climate Change Special Initiative Energy Efficiency: McKinsey & Company.

[19] Saaty, T., 1994, "How to make a decision: The analytical hierarchy process", INFORMS: Institute for operations research and the management sciences, 24/6: 19-43.

[20] Saaty, T., 2004, "Fundamentals of the analytical hierarchy process – multiple networks with benefits, costs, opportunities and risks", Journal of systems science and systems engineering, 13/3: 348-379.

[21] Saaty, T., 2004, "The analytical hierarchy and network processes", Journal of systems science and systems engineering, 13/1: 1-35.

[22] Kellens, K., Dewulf, W., Overcash, M., Hauschild, Duflou, J., 2012, "Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) - CO2PE initiative", The international journal of life cycle assessment , 17/1: 69-78.

[23] Aughney, N., O'Donnell, G. E., 2012 "Lean Energy: A methodology to characterize and optimize energy and resource consumption within manufacturing process chains", *Proceedings of the 10th global conference on sustainable manufacturing (CIRP)*, pp718-723.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

9.5 Performance adaptive manufacturing processes in an energy efficient car production

T. Creutznacher [1], R. Lepratti [2], S. Lamparter [1], G. Heinecke [1]
[1] Siemens Corporate Technology, Munich, Germany
[2] Siemens Industry, Nuremberg, Germany

Abstract
Energy efficiency is of increasing importance towards sustainable manufacturing in the automotive industry, in particular due to growing environment regulations and rising electricity costs. Approaches within the manufacturing planning phase are insufficient to address dynamic influences during run-time (e.g., electricity tariffs or workload). Additionally, conventional production monitoring and control systems consider the 'Overall Equipment Effectiveness' of manufacturing systems, but do not include related energy efficiency. This paper introduces a novel approach that combines these both aspects and provides more effectiveness based on so-called production variants. The latter are designed during the planning phase and used to adapt manufacturing behavior when facing dynamically changes during run-time. A simulation shows how dynamic adjustments of cycle times lead to a high reduction of energy costs while maintaining high throughputs.
Keywords:
Energy efficiency; performance adaptive production; production planning and control

1 INTRODUCTION

Sustainability has become increasingly important in the last years. The efficient management of resources is indispensable to globally address the ambitious environmental targets and economical growth. This is one of the key aspects of the European growth strategy 'Europe 2020' [1] as well as of the German 'Industrie 4.0' initiative focusing on next generation production systems. In the future 'Smart Factory', sustainability will be as important as productivity. A great contribution to the environmental goals is expected to come from the car manufacturing industry, both in terms of energy efficient cars as well as manufacturing processes. European car manufacturers have already started important initiatives. For example, Volkswagen AG launched the 'Think. Blue Factory.' project with the goal of improving ecologically friendliness of its factories by 25 % until 2018 [2].

This paper is addressing energy efficient car production by enabling performance adaptive manufacturing processes that support a wide range of alternative production modes with different energy consumption profiles. Enhancing manufacturing IT systems with such profiles allows dynamic adaptations of production processes based on run-time information such as electricity prices, resource availability, workload, and buffer utilization. In particular, the paper focuses on how complementary production variants can be designed, how they can be deployed to manufacturing IT, and how optimal variants can be selected by product control algorithms during run-time. The latter has to consider performance measures beyond traditional Overall Equipment Effectiveness (OEE) key performance indicators (KPIs) covering also energy-related aspects [4].

The remainder of the paper is structured as follows. In chapter 2 the main challenges to realize energy efficient production systems in the automotive industry are discussed. Existing work regarding solutions for these challenges is reviewed in chapter 3. Chapter 4 introduces the concept of performance adaptive manufacturing which is evaluated in chapter 5 regarding its impact on production KPIs. Chapter 6 concludes the paper with a short outlook.

2 PROBLEM DESCRIPTION

A typical car factory consists of press shop, body shop, paint shop, powertrain and assembly. Especially the carbody shop has a large demand in electricity, because of its high degree of automation (see Figure 1).

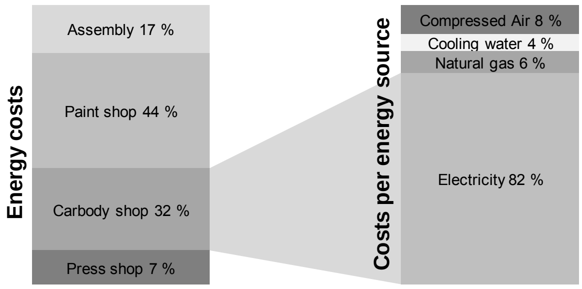


Figure 1: Energy costs per shop, based on [5].

Energy consumption is not just a static quantity; it has also a temporal progress. In order to reduce the total energy consumption in a long- and medium-term period, similarity patterns in the average consumption (uniform peaks in Figure 2) can be recognized and optimized in the planning systems of product lifecycle management (PLM). During run-time, however, this is typically done in enterprise resource planning (ERP) systems. Long- and medium-term planning has two major drawbacks. First, the volatile environment of energy consumption (irregularity of consumption in detailed view of Figure 2) caused by dynamic and complex influences, e.g., from the supply chain, can hardly be predicted, but have to be determined at run-time. Second, flexible electricity price tariffs, which will be introduced with the upcoming Smart Grid, will provide real-time price signals that cannot be used in the

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

long- and medium-term planning. For that reasons energy efficiency has to be considered in the short-time detailed production planning, which is usually done by manufacturing execution systems (MES). Today, detailed production planning approaches consider OEE, which only consists of availability, performance and quality, but not of energy consumption and prices [6].

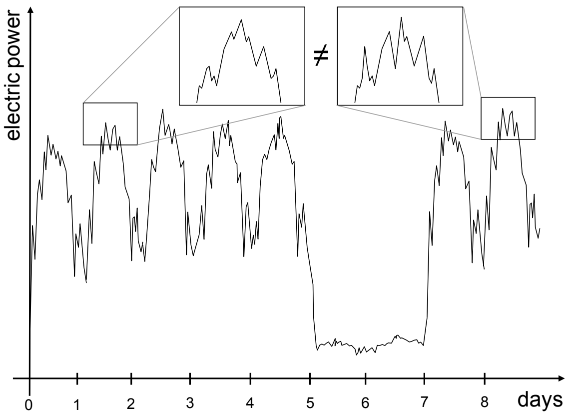


Figure 2: Characteristic energy consumption of a car production over one week.

In addition, a MES requires a high degree of flexibility to react on the volatile environment. Today, the flexibility is restricted by the fixed production process that is specified by PLM systems at design time and cannot be changed during run-time. In order to increase flexibility during run-time, different variants of production processes have to be designed in the PLM tools and made available to the MES. However, designing the most relevant production process alternatives is a complex task. For example, the large number of installed robots in a body shop enables a high flexibility, but requires also taking care of complex relationships along the process. A high number and diversity of possible variants, just-in-time and just-in-sequence logistics combined with lean management are additionally complicating the production process design.

Existing approaches to address these challenges are discussed in the following chapter.

3 RELATED WORK

Energy efficiency has to be addressed on all production levels from the machine level [17] to the multi-facility and supply chain level [7]. For a general overview of approaches see [18]. Today energy efficiency in terms of decreasing the total power consumption of manufacturing processes with unchanged output nearly is a exclusive topic of the ‘factory design‘ phase of the PLM and especially of the so-called digital factory. The German innovation alliance ‘Green Carbody Technologies‘ [3] researches the forecasting and optimization of the energy consumption by PLM tools, e.g., by the use of simulation of systems in materials handling including energy efficiency. On the one hand there are 15 % possible savings in energy consumption by the optimization of complete facilities. On the other hand optimizations on machine level leads to a statically energetic optimized operating like energy efficient robot movements with up to 30% possible savings in energy consumption.

Energy efficient control during run-time is a quite new area of application and is always based on measurement and monitoring of energy consumption on machine level. Suitable sensors or other measurement instruments can permanently record energy consumption over time. Other possibilities are single representative measurements or forecasting by simulation. These methods allow energy monitoring for single processes and control programs. Energy monitoring needs KPIs, which are currently standardized [7]. They are also required for applications on control level in order to identify weak points or correlations between operating modes and energy consumptions [8].

There are holistic approaches for energy efficiency during run-time [9], but most researches are based on conventional planning tools. Especially tools of the digital factory provide innovative solutions like combined simulations of material and energy flow [10, 11]. Another possibility is the development of an energy efficiency based production control [8] and superior energy control systems. Possible application scenarios are found in avoiding peak loads, reducing no-load losses or shift secondary processes into low-rate periods. Shutdown concepts should also be mentioned [12] which focus on energy saving in non-productive phases of a factory.

This paper in contrast deals with energy efficiency during the operating phase by performance adaptive manufacturing processes supported by tools of the digital factory.

4 PERFORMANCE ADAPTIVE MANUFACTURING PROCESSES

Electric energy consumption depends for a big part on the specific movement of a machine. For the same path and different operation speeds there is always a characteristic graph of the required electric power as a function of the operating speed. For example, the energy consumption of a robot movement describes a bathtub curve (see Figure 3).

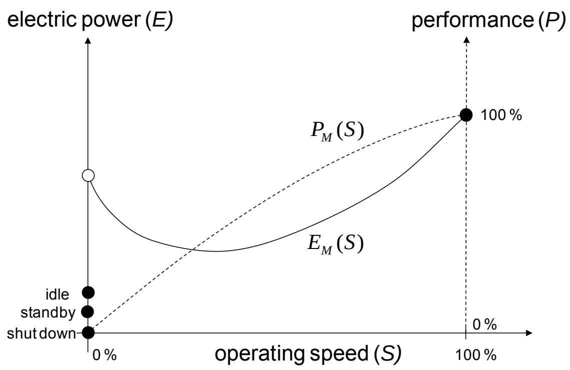


Figure 3: Power consumption and machine performance of a machine *M*, based on [13].

Until now robots are using only the four marked operation modes shutdown, standby, idle and full speed. The full flexibility of operating speed and performance is not used during the movement. In general a robot has low energy consumption in idle mode, which is equal to the part of energy, which is independent of movements. At slow speed it disproportionately needs much energy. The energy consumption is decreasing until a local energetic minimum, because of the utilization of inertia. With higher speed the energy consumption is progressively increasing, because a double operating speed needs a four times higher kinetic energy. The performance (output) behaves nearly linear, but doubling speed does not mean doubling performance, because of unchangeable fix time slices like set-up times or runback times of sensors and actuators. In conclusion slower manufacturing processes are reducing performance, but need overall less energy.

Because not all machines are able to adapt their speed/performance, this paper focuses on highly automated manufacturing processes in subsections like body shop, power train or paint shop, where motion typically is a part of manufacturing (e.g., material handling systems, robots, CNC milling). Slower, less productive processes can be utilized in certain situations, when full speed is not always the best option, e.g., internal influences like the unavailability of material at previous production steps or foreseeable bottlenecks at following stations. Machines which are not in the critical path also do not necessarily need to run at full speed. External influences like an adaptation to volatile price of electricity or already in chapter 3 mentioned scenarios, like avoiding peak loads, are also reasons for performance adaptive processes. The traditional ineffective answer on such problems was to shut down the entire line and deal with high restart times or rework single products.

In the following, performance adaptive manufacturing processes are presented to handle dynamic influences. Figure 4 shows the major components of the approach. After production design and engineering (PLM) and virtual commissioning, the alternative production variants supported by the control programs are evaluated (chapter 4.1). A suitable subset of these variants is then stored in a library which is accessible by the run-time manufacturing IT (chapter 4.2). For utilizing these variants during operation the short-term production planning algorithms have to be extended (chapter 4.3) in order to enable them to select the most appropriate variant by an MES for a given production situation (e.g., production program, electricity price, machine utilization). The plant automation in the shop floor then is executed and monitored by a hierarchic structure of programmable logic controllers (PLCs), robot controls (RCs) and computer numeric controls (CNCs).

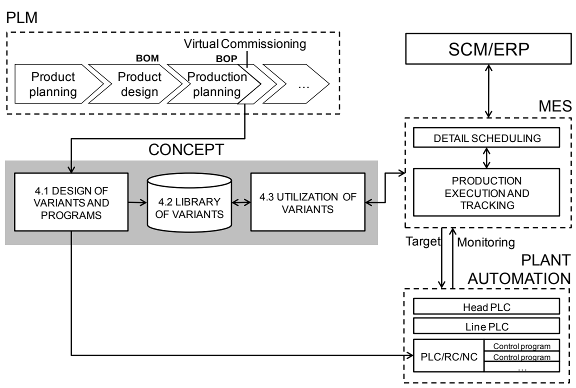


Figure 4: Concept of performance adaptive manufacturing processes.

4.1 Design of variants and programs

Performance adaptive manufacturing starts already during the production planning. In this context, various IT systems and tools are used for the design and engineering of run-time components. These systems have to be extended at various points to support performance adaptive processes. The conventional design of a production starts with initial product and process information like bills of material, manufacturing technologies and production quantities. Amongst others the tasks of production planning are the creation of a bill of process (BOP), the selection of machines and the planning of capacity, material flow and factory layout. Virtual commissioning is the last step of production planning, which also serves automatic program generation for PLCs, RCs or CNC. Information about machines (e.g., attrition) and processes (e.g., maximum speed) as well as about complex dependencies between the different components of the machine are considered for the program design. Such information is typically not available in the later stages of the product or production lifecycle and in particular not in the run-time systems. Therefore, the upfront design of alternative operating variants that provide flexibility to the later manufacturing IT is important.

For defining the operating variants for a performance adaptive production process we first have to take a closer look at the specific presupposed energy consumption curve of each machine (cf. Figure 3). Under the assumption that the energy consumption of a machine $E_M(S)$ depends solely on its own configuration and not on the configuration of the other machines in the line, the energy consumption of the line L can be calculated by $E_L(S) = \sum_{i=1}^{n} E_{M_i}(S)$. In the field of automotive industry, there are fixed cycle times for every line, which are independent from product variants. Slower process execution S means higher cycle times C. Different machines along a line have to be configured for the same cycle times as long as no buffers are available between machines (or lines). If a buffer is available cycle times of two lines can be different, i.e., $C_{L_1} \neq C_{L_2}$ for the two lines L_1 and L_2 connected with a buffer, but $C_{M_1} = C_{M_2}$ for two machines without buffer. This concept is exemplified in Figure 5.

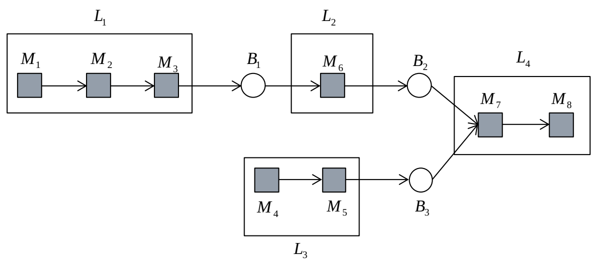


Figure 5: Structure of a production system.

As different lines can be operated independently with different operating speed, operating variants have to be defined for each line separately. Therefore the line-specific function for the energy consumption $E_L(S)$ is calculated using the consumption profiles of each machine in the line. Figure 6 shows a simplified example for the body shop where electricity demand is mostly generated by robots. It is supposed that the curve is continuous and has only one minimum.

In many cases the number of possible variants that can be configured is extremely large (e.g., due to continuous parameters in the control program). However, the number of the variants has to be restricted in order to reduce the programming effort and allow an efficient selection of the most suitable variant during run-time. Therefore, a pre-selection of the most important variants has to be done in the design phase. A variant is important if there could be a situation during run-time, where the performance (KPIs including energy demand) can be improved by selecting it. Thus, system performance as combination of e.g., energy efficiency and throughput (BPI) [4] can be improved by adding this variant. In the first place this statement holds for all variants that are located at minimum or maximum points regarding energy consumption or cycle time. During run-time the fastest and slowest possible variants as well as the variants with the lowest and the highest consumption are required (variants v_1, v_3 and v_5 in Figure 6). A high consumption variant could be necessary even if it is not the fastest variant in case of negative electricity prices which can be possible in demand response scenarios.

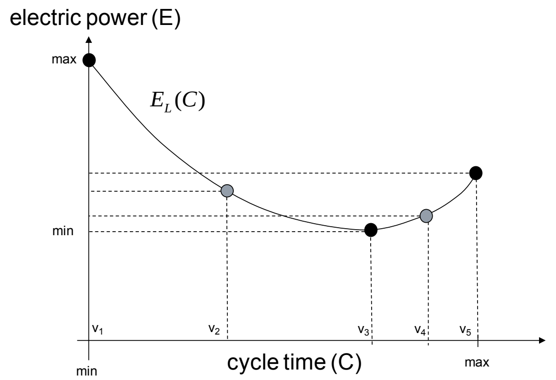


Figure 6: Selection of line operating variants with different discrete cycle times.

In addition, to these basic variants additional operating variants can be designed to enable a more fine-grained optimization approach during run-time (variants v_2 and v_4). However, too many variants lead to an explosion of the solution space (e.g., 4 lines with 5 variants each support already 3125 different production processes). Therefore, the number of variants is a trade-off between the additional computational complexity and the benefit. The additional benefit depends on the degree of difference in terms of energy consumption of the new variant v_{new} compared to the existing variants V. As a guideline for assessing the number of required variants the following formula can be used:

$$v_{new} := E_L^{-1}\left(\frac{E_L(v_i)- E_L(v_{i+1})}{2}\right)\ if\ |E_L(v_i) - E_L(v_{i+1})| > SF,$$

with $v_i \in V$, the inverse function E_L^{-1} and the parameter SF representing the minimum energy saving factor. The smaller the parameter SF is chosen the more variants will be generated making sure that variants are chosen for areas with strong differences in energy consumption (i.e., first derivative $|E_L'(C)| \gg 0$). Note that this approach might lead to variants with similar energy consumption but different cycle time. This is required to address situations where cycle times are very restricted and still options regarding energy consumption are required.

This approach does only consider productive phases. Therefore, standby modes or the complete shutdown of machines are not considered as variants in this concept. The topic of energy efficient control of production lines in non-productive phases is discussed in [12].

In the next step the control programs for the required variants have to be realized and manually transferred to the respective controllers (PLC, RC or CNC). For example a robot gets five speed adaptive programs, planned with PLM tools in a movement simulator and transferred to its RC controller. In conclusion the robot does not longer have only two options of full speed or idle. It is now able to choose between five programs or variants with different operating speeds and idle, standby or shut down mode.

4.2 Library of variants

The library of variants is a database containing a description of the specified variants and serves as an interface between the PLM planning systems and run-time manufacturing IT. The library is completely filled at design time and can be constantly accessed during run-time. As shown in Table 1, variants are assigned to each line, process and the line's machine control programs. Furthermore they specify the expected energy consumption as well as cycle times, and define the product for which a variant can be used. Transports between process steps can also be included. The total factory performance can now be calculated by the cumulated cycle times during the run-time. The electric power will be declared instead of energy consumption for idle modes.

Table 1: Library of variants

Variant	Line	Process	(Machine / Control Program)	Product	Energy con-sumption	Cycle time
V1	L1	Welding	(M1, CP2), (M2, CP5)	P1	51 kWh	30 s
V2	L1	Welding	(M1, CP3), (M2, CP4)	P1	30 kWh	40 s
V12	L6	Bonding	(M32, CP3)	P2	32 kWh	40 s
V63	L12	Transport	(M44, CP5)	P1	1 kW	Idle
...						

4.3 Utilization of variants

The library of variants provides additional flexibility to the detailed production scheduling done by the MES. Detailed production scheduling has to be extended beyond production order sequencing in order to additionally select the most suitable process variant for each line given in a certain production situation. The production situation is defined by a set of variables that can be observed or measured during runtime. These variables include:

- the current and future production program
- the current electricity tariff
- unexpected events such as machine breakdowns or JIS/JIT failures
- current capacity of buffers

Generally, long-term changes of variables are addressed by the ERP system and medium-term changes can be handled by a dynamic, event-driven order sequencing approach as outlined in [14]. In the following, we focus on short-term adaption of line-specific cycle times through selection of the most appropriate variant from the library considering not only throughput but also energy-efficiency. The goal is in that context to select one of the Pareto-optimal variants.

Optimal selection of the variants requires a robust prediction of variable values above (e.g., future electricity prices). Given such predictions, a dynamic programming approach could be used to calculate the optimal production processes. However, as correct predictions are not possible, optimization approaches will lead to suboptimal results. In addition, optimization approaches are sometimes not intuitive for the line operators because understanding the solution can be highly complex. Therefore, in the following a rule-based approach is proposed that is based on fuzzy logic [15, 16]. One the one hand, fuzzy rules have the advantage that their evaluation is extremely fast and can be easily done during run-time (even for large solution spaces). On the other hand, they are quite intuitive for operators due to the usage of linguistic variables (e.g., expensive, cheap) and more robust to imprecise predications of traditional rule-based systems.

The application of fuzzy rules requires defining membership functions that map continuous variables to fuzzy sets which are described by linguistic variables. Figure 7 exemplifies this ‘fuzzification‘ for the variable electricity price. In a similar way, also the variables that reflect the available capacity of the buffers and delay of input material can be mapped to fuzzy sets. Discrete variables with a low number of values (such as the variants) can be used in the rules without fuzzification.

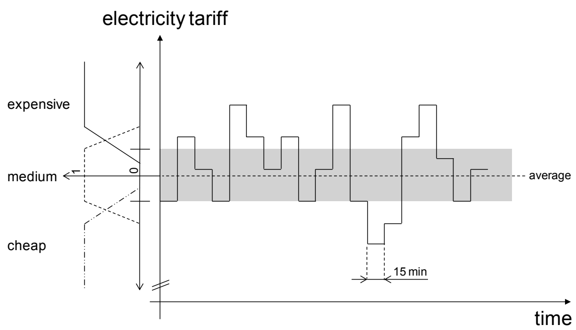


Figure 7: Fuzzification of electricity price.

Based on the fuzzy sets rules, it can be defined by the operators how the system should react on changes in variable values. E.g., the operators can define that variant v_4 should be used for line L_1 if electricity prices are ‘*expensive*‘, buffer capacity B_1 is not ‘*scarce*‘ and utilization is ‘*low*‘. If in the same case utilization is ‘*high*‘, variant v_2 would be more appropriate. The degree of fulfillment of a rule and defuzzification are calculated as proposed by [16]. Usually it is sufficient to define one rule for each production line and variant, but of course also more detailed reactions can be configured via such rules. Obviously, the approach is a heuristic and typically will not lead to an optimal solution. However, a complete optimization would also lead to a suboptimal solution (due to uncertain predictions).

In the next section the concept is evaluated regarding the performance of an automotive production line.

5 EVALUATION

To evaluate the concept of performance adaptive production lines, a simulation model was built in Plant Simulation 9.0 based on the production system in Figure 5. Table 2 lists the parameters with their respective categories that were implemented into the model in a morphological box. Most importantly, we define four variants that vary the operation speed of each production line from its maximum value to its half. Similar to the preceding outlines, the highest speed is associated with the highest energy consumption while the lowest speed requires the least energy. Also, in accordance with Figure 3, a small decrease in speed from a high performance level is accompanied by a disproportionally large drop in energy consumption. Conversely, a large decrease in speed at low levels results only in a small drop in consumption.

To evaluate the performance of utilizing multiple variants, line performance (i.e., speed) is subjected to considerations regarding external energy prices and internal in-process inventory levels. First, the energy price for the simulation was derived from hourly price data over half a year from the spot market of the European Energy Exchange. Using the maximum likelihood method, the values were fitted to a normal distribution with a mean of 41.82 €/MWh and standard deviation of 12.92 €/MWh. In accordance with Figure 7, Table 2 shows the division of the price range into four categories from cheap through expensive. The energy price in conjunction with adaptable speeds allows the deceleration of production when prices are high. Second, the three buffers of the production system in Figure 5 allow for the measuring of the work in process (WIP) inventory. Again, Table 2 shows that the WIP level for each buffer was also divided into four categories. The WIP level of subsequent buffers in conjunction with adaptive speeds of preceding lines allows to slow production when the buffer is full, implying that the following lines do not cope with the current workload.

Table 2: Categorization of parameters

Parameter	Categories			
Operation speed	Slow (50%)	Medium (70%)	Fast (90%)	Maximum (100%)
Energy price	Cheap (<30 €/MWh)	Low-end (30-40 €/MWh)	High-end (40-50 €/MWh)	Expensive (>50 €/MWh)
WIP level	Empty buffer (<5 units)	Low buffer (5 - 9 units)	High buffer (10-14 units)	Full buffer (>14 units)

The simulation ran for 100 days and was implemented with three strategies – WIP, energy price and a hybrid strategy. The latter balances the other two factors. The results are displayed in Figure 8. The strategies are compared against the full productivity scenario where all production lines of the system run at maximum speed to achieve the highest throughput performance. Considering the energy costs per unit, all strategies are superior to the baseline scenario. Intuitively, the strategy that focuses solely on the energy price outperforms all others, cutting energy costs per unit almost by half. The same is true for the energy costs that accumulated over the 100 days. However, considering the actual system output, the price-based strategy performs poorly with only 70% of the output of the baseline strategy. It slows production whenever prices are high and thus, is completely subjected to the random fluctuations of the energy price. Although it is not applicable to real-life scenarios, the price-based strategy illustrates the scope for energy efficient production lines. The WIP-oriented strategy neglecting energy prices results in the highest energy and unit costs but achieves a significantly higher output than the price-based strategy.

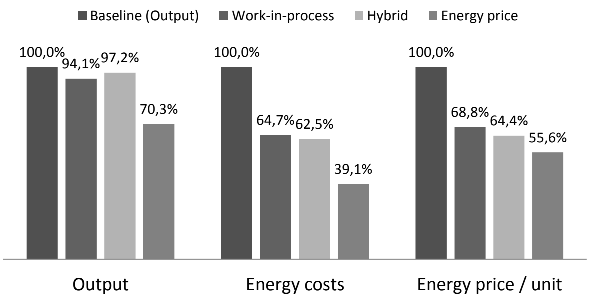


Figure 8: Comparison of results.

The best performance is recorded for the hybrid strategy. It combines the constraints of the other strategies by producing at full speed whenever energy prices are low or the subsequent buffer is starved. Conversely, it produces at slow speeds whenever the price is high or the subsequent buffer is close to full. Figure 9 illustrates this connection: Whenever the energy price is low, the system produces at full speed, which subsequently increases the total WIP level of the system. Conversely, when the price peaks, the system slows down and the WIP-level is reduced. Figure 8 shows that the hybrid strategy achieves a higher output than all other strategies at lower energy costs than the WIP-based strategy. Furthermore, it comes close to the ‘optimum’ of the full productivity scenario while reducing energy costs considerably.

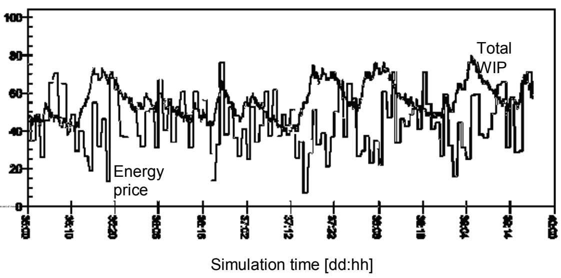


Figure 9: Price versus total WIP level.

6 SUMMARY AND OUTLOOK

It has been shown that performance or speed adaptive manufacturing processes increase energy efficiency and sustainability. The approach was realized during run-time and supported by PLM planning tools. A library of variants works as an interface and provides different energy consumptions for several production variants and cycle times. The variants can be dynamically requested during run-time.

Prospective researches will deal with a higher diversity of variants and complexity. The temporal progress of energy consumption will be provided more detailed and simultaneous simulations will be used during run-time.

7 REFERENCES

[1] European Commission, 2010, Communication from the commission – Europe 2020 – A European strategy for smart, sustainable and inclusive growth

[2] Volkswagen AG, 2011, press release nr. 451

[3] Wagner, E., 2012, Vorhersage schafft Einsparungen, KEM, August edition

[4] Berger, U., Creutznacher, T., Lepratti, R., Lamparter, S., 2013, Optimierung von Fertigungsprozessen der Automobilindustrie durch PLM-MES-Kopplung mittels Balanced Performance Indicator, Vernetzte Automation in funkbasierten und kabelgebundenen Netzen

[5] Engelmann, J., 2008, Methoden und Werkzeuge zur Planung und Gestaltung energieeffizienter Fabriken

[6] ISO/DIS 22400-2, 2012, Automation systems and integration – Key performance indicators for manufacturing operations management

[7] ISO 50001, 2011, Energy management systems – Requirements with guidance for use

[8] Müller, E., Löffler, T., 2009, Improving Energy Efficiency in Manufacturing Plants – Case Studies and Guidelines, CIRP International Conference on Life Cycle Engineering, 16:465-471

[9] Weinert, N., 2010, Vorgehensweise für Planung und Betrieb energieeffizienter Produktionssysteme

[10] Berger, U., Wolff, D., Kulus, D., 2012, Einsatz digitaler Techniken zur Steigerung der Energieeffizienz in der Automobilindustrie, zwf-online, inpro-Innovationsakademie, 107:587–590

[11] Putz, M., Schlegel, A., Lorenz, S., Schulz, S., & Franz, E., 2011, Gekoppelte Simulation von Material-und Energieflüssen in der Automobilfertigung. Proceedings of the 14. Tage des Betriebs- und Systemingenieurs.

[12] Mechs, S., Müller J.P., Lamparter, S., Peschke, J., 2012, Networked Priced Timed Automata for Energy-Efficient Factory Automation. In 2012 American Control Conference (ACC 2012), Montreal, Canada.

[13] Pellicciari, M., Berselli, G., Leali, F., Vergnano, A., 2013, A method for reducing the energy consumption of pick-and-place industrial robots, IFAC, Mechatronics, 23:326-334

[14] Heinecke, G., Köber, J., Lepratti, R., Lamparter, S. Kunz, A., 2012, Event-driven order rescheduling model for just-in-sequence deliveries to a mixed-model assembly line, In Proc. of Advances in Production Management Systems (APMS), Rhodes Island, Greece.

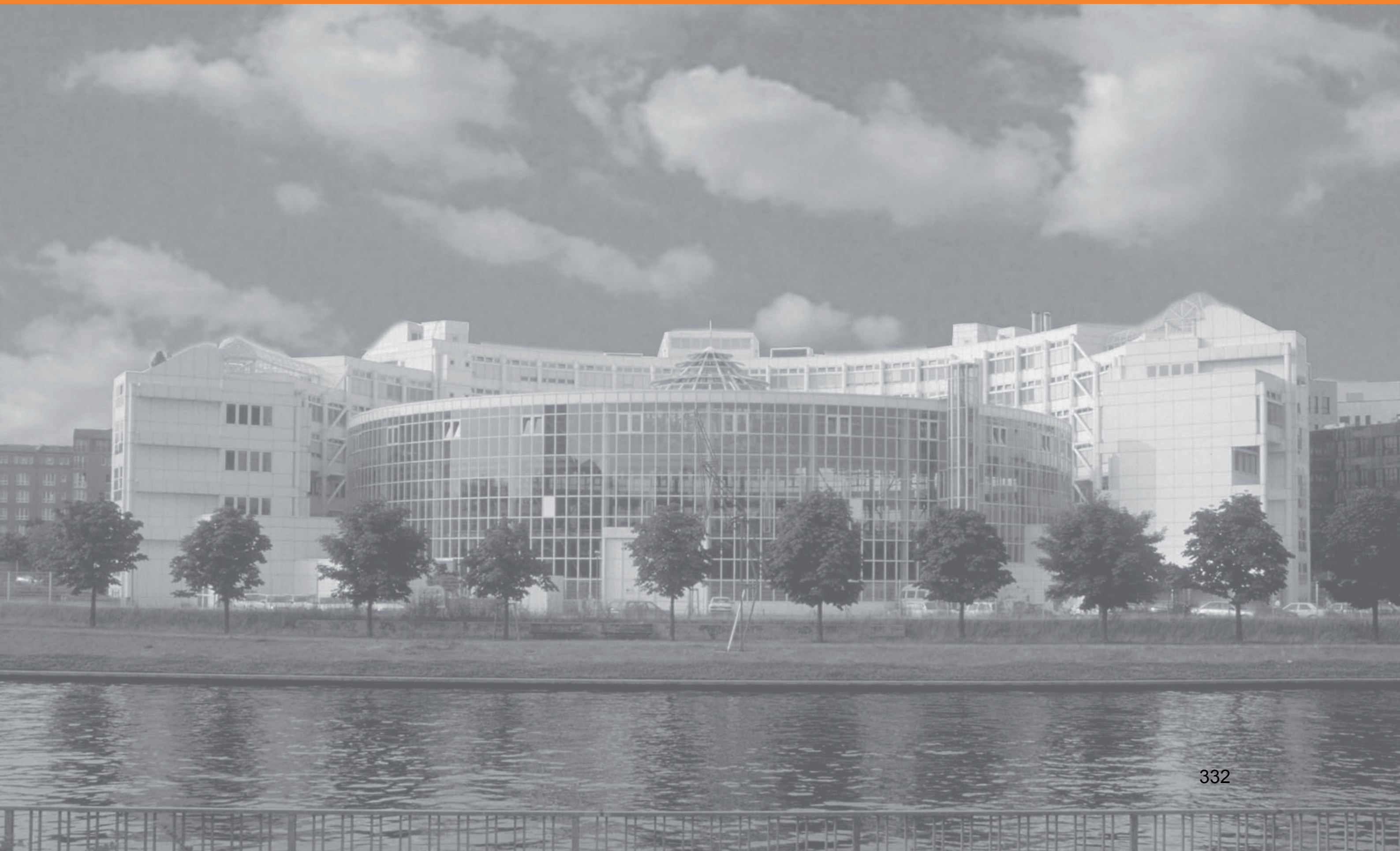
[15] Lotfi A. Zadeh, Fuzzy Sets, Information and Control, 8, 1965:338-353

[16] Agarwal, S., Lamparter, S., 2005, sMart – A Semantic Matchmaking Portal for Electronic Markets, G. Mueller, K.-J. Lin (Eds.): IEEE International Conference on E-Commerce Technology, 7:405-408

[17] ISO 14955: Environmental evaluation of machine tools – Part 1: Design methodology for energy-efficient machine tools

[18] Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012, Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals - Manufacturing Technology, 61/2:587-609

Session 10
Remanufacturing



10.1 Closed and open loop recycling of aluminium: A Life Cycle Assessment perspective

Dimos Paraskevas[1], Karel Kellens[1], Renaldi[1], Wim Dewulf[1,2], Joost R. Duflou[1]
[1] Department of Mechanical Engineering, KU Leuven, Belgium
[2] Group T – Leuven Engineering College, KU Leuven Association, Belgium

Abstract

Compared to other base metals, the refining options for aluminium during the final metallurgical recycling stage are very limited. These limited melt purification options, along with the relatively large number of alloys and the accumulation of alloying and foreign elements during the different life cycle stages, force the aluminium industry to operate in a cascade recycling chain. A Life Cycle Assessment (LCA) based, resource oriented approach, is presented in order to: i) assess the environmental impact calculation during aluminium recycling, ii) examine the scrap recycling loops and iii) express and quantify dilution and quality losses during recycling. Finally, this paper discusses, from an environmental point of view, strategies and opportunities for improved recycling as well as opportunities for more sustainable scrap management. Case studies focusing on major post-consumer scrap streams are examined based on their environmental performance in two different recycling scenarios.

Keywords:

Life Cycle Assessment, Cascade, Aluminium Recycling, Resource Efficiency

1 INTRODUCTION

Compared to other material categories, metals have the highest potential for systematic recycling, due to i) their high economic value, ii) their large volumes enabling economies of scale and iii) their distinctive feature of excellent recyclability. Nevertheless, many challenges related to the accumulation and mixing of alloying elements due to inefficient alloy separation and accumulation of impurity elements (also known as tramp elements) during the different life cycle stages, along with the removal limitations of certain elements during smelting processes, are still not properly addressed.

Except for aluminium foil, aluminium is not used in its elemental form, but rather as an alloy. More than 450 alloy designations/compositions have been registered by the Aluminium Association Inc. [1]. Typical alloying elements depending on the alloy series are: Si (Silicon), Cu (Copper), Zn (Zinc), Mg (Magnesium) and Mn (Manganese), with Fe (Iron) occurring mainly as an impurity element. Two major categories are defined with respect to the concentration of alloying elements: i) high purity wrought alloys (with alloy content up to 10%) and ii) cast alloys with much higher tolerance limits for alloying elements (with alloy content up to 20 wt.%), especially for Si. The relatively broad variety of alloys, combined with the often inefficient pre-melt alloy separation, leads to higher entropy scrap streams (a mixture of several alloys) that are difficult to handle.

Nowadays, this challenge is successfully addressed either by dilution of the difficult to handle impurities with high purity metal inputs, or by cascade recycling to alloys with lower purity requirements. Since there is limited scrap availability and at the same time a high demand for highly alloyed products (cast and die cast alloys), both strategies effectively address this industrial problem. Nevertheless, one can wonder whether these strategies will remain sustainable solutions in the future.

2 CHALENGES IN ALUMINUM RECYCLING

2.1 Refining options and limitations

Recent studies [2,3], based on chemical thermodynamic analysis simulating smelting processes, indicate which elements can be removed and in how far impurity can be controlled during recycling of various base metals, such as, aluminium, steel, copper and magnesium. Nakajima et al, [2] examined the distribution of 45 elements (most of them occur as tramp elements) in the gas/metal and slag/metal phase for simulated aluminium remelting. In most cases melt purification can be performed either through the oxidation mechanism in the slag phase or by evaporation in the gas phase. The authors concluded that, amongst the examined elements, only Mg, Ca and Be can be removed in the slag phase, and Zn, Cd and Hg in the gas phase under varying oxygen partial pressure and temperature conditions. Regarding the contamination by the typical alloying elements, only Mg (in the slag phase) and Zn (in the gas phase) can be removed to an appreciable extend. The residual 39 elements remain in the metal phase. In consequence the purification of the melt from the elements that remain in the metal phase during the final recycling step processes is either very difficult or essentially impossible to achieve. Moreover, while a post electrolysis process can recover most of the impurity elements that remain in the metal phase during smelting of copper, this is not the case for aluminium. Compared to the primary production of aluminium, consuming, approximately

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

14 kWh/kg, the three layer electrolytic process for aluminium refining is more energy intensive with a consumption of 17-18 kWh/kg [4].

Flux treatment is the most common and widely used melt liquid metal treatment in industry since it: i) reduces oxidation, ii) removes hydrogen and nitrogen gases, and iii) removes Ca, Sr, Na, Mg and Li inclusions from the melt [4]. Moreover, a flotation/de-gassing treatment of the melt, purging gases containing chemical reactive components such as chlorine gas, can also be an effective solution in removing Na, Ca, Li and Mg apart from hydrogen [5]. Zinc, a major alloying element in the 7XXX alloy series, can be recovered using distillation technologies [4]. Finally, other technologically advanced melt/chemical separation technologies, like fractional crystallization and unidirectional solidification, are still in a research or early development stage [5]. Thus, from technical and economic point of view, these technologies are still questionable and not proven to be viable for scrap purification at large scales.

2.2 Scrap Sorting

New scrap from production can be separated into two categories according to its source: i) semi-manufacturing and ii) manufacturing scrap. The forming scrap from the semi-manufacturing sector (e.g. extrusion and rolling scrap) concerns relative large and homogeneous flows where the benefit of knowing the chemical composition is partially utilized by recycling internally by integrated cast houses. These scrap streams are usually not available in the scrap market. Thus, more opportunities for more sustainable scrap management and added scrap value by sorting can be found in the product manufacturing scrap and in urban mining where the composition uncertainty due to alloy mixing is at higher levels. Inefficient pre-melt scrap sorting in product systems containing both fractions (like automobiles) will result in the wrought alloy fraction to be lost in the cast fraction. Table 1 presents the Si content of blended wrought and cast alloys for various mixing ratios. By mixing wrought/cast alloys in increasing ratios, the concentration of Si in the scrap stream is increased and thus lowering the scrap quality in terms of recyclability. Increased concentrations of a contaminant results in limited options for cascade or higher dilution needed to up-cycle to higher purities leading to underutilization of the scrap. Alloying elements, such as Si, are essential elements; but the when different alloys are mixed in an uncontrolled manner, they can became contaminants.

Table 1: Average Si content for various blended wrought cast fractions [5].

Wrought/Cast ratio	Average % Si
1/5	8.0
1/1	5.0
2/1	3.5
5/1	2.0
10/1	1.3

The recovery of embedded financial value of the scrap stream composition can be positively affected by a recycling strategy based on separate recycling of different alloy categories/series. Taken into account also the economic benefits from this separation, regional standards are being established in order to control the scrap quality. In the European Community, the DIN EN 13920 standard [6] identifies 15 different categories of aluminium scrap. Similar scrap categorisation systems, but focusing more on scrap from different product systems, can be found also in other countries [7]. Thus, any scrap dealer or trader supplying sorted scrap according to these standards can set a higher price and therefore obtain a commercial advantage. Moreover, the impact of scrap usage is inversely proportional to the production cost and by increasing scrap utilization the overall production cost can be reduced [8].

2.3 Recycling Circuits and Options

To resolve the challenges linked to poorly managed scrap streams, the Aluminium industry makes use of a cascade recycling chain. In Figure 1a a simplified representation of an aluminium cascade chain is depicted. A graphical representation of the pathways for industrial scrap (yield loss of the production), and for post-consumer scrap according to their recycling options is shown in Figure 1b.

Unalloyed/low alloyed Al (1XXX series), coming from primary Al, can be considered at the top of the chain as high purity (in terms of Al content) products. Wrought alloys are in the middle of the chain, while alloys with low purity requirements alloys act as a sink in the cascade recycling stage. Since wrought alloys have strict and very low tolerance limits for alloying elements, their production is heavily dependent on primary Al consumption. Mixed alloy scrap streams are difficult to be absorbed into a wrought product due to mixing and excess concentrations of alloying elements. For that reason downgraded or mixed alloy scrap streams are mainly diverted to cast alloys. A common practice nowadays is to down-cycle mixed wrought alloys to cast quality. For primary Al there is no restriction of utilizing it to produce any alloy by adding alloying elements, and since there is limited scrap availability, primary Al is used as high purity metal input to balance the cascade chain. Figure 1a,b represents the recycling options and the recycling loops of the scrap streams according to the quality of the input/output (I/O) metals that are investigated from an environmental perspective. These recycling options are:

Preserving quality **:** Meaning that the quality of the scrap streams is effectively controlled and recycling is performed in a compositionally closed recycling loop, without any significant change in the inherent properties (alloy content) between the input and output materials. The single alloy strategy (illustrated by the green line in Figures 1a,b, represents the completely closed compositional recycling loop, effectively avoiding the need for dilution and quality degradation. The environmental impact per kg of produced alloy is minimal and can be mainly attributed to the energy requirements of the recycling process itself.

Downcycling : Accumulation of impurities and alloying elements to alloy products with lower purity requirements, when higher purity secondary resources are used to produce lower purity products (e.g. transition from mixed wrought alloys to cast quality).

Upcycling: When impurities are diluted with high purity metal inputs. Taking into account the limited scrap availability and high demand for cast alloys, the dilution agent is primary Al, especially for wrought aluminium production.

From economic point of view the high purity metal in the case of dilution, as well as the reduced product value in the case of

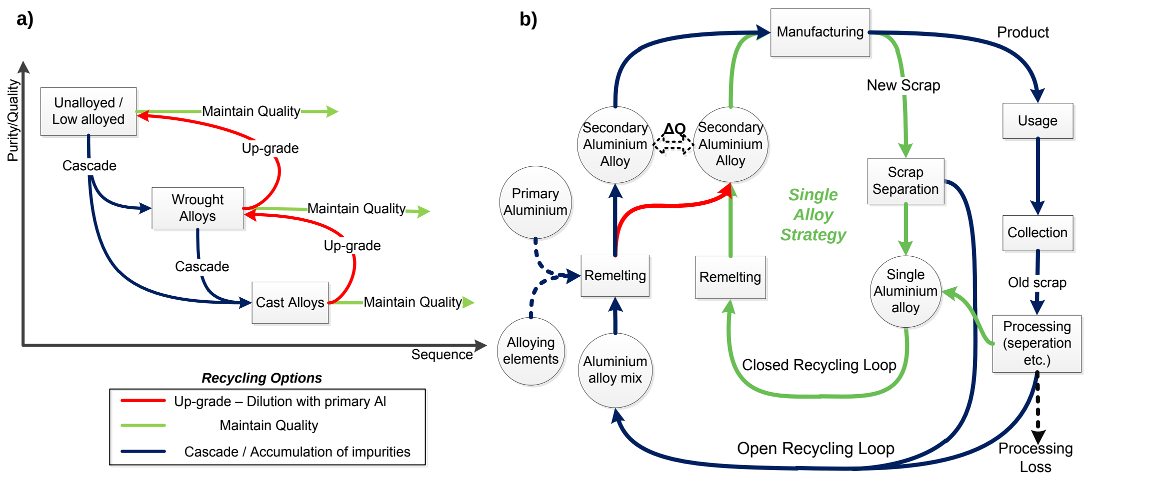


Figure 1: a) Al Cascade recycling chain and b) Recycling options and corresponding pathways.

down-cycling form incentives towards more efficient quality preserving solutions.

2.4 Resulting Challenges

In recent years increased concern has risen from researchers regarding the sustainability of the currently used industrial recycling strategies. A recent study [9] indicates that the introduction of electric vehicles will result in a decrease of the demand for cast alloys, generating 6.1 Mt of scrap in 2030 which will not be recycled due to the high concentration of alloying elements. The same research group forecasts a surplus of 12.4 Mt of scrap with high alloy content in 2050 that will not be able to be recycled. Modaresi and Muller [10] developed a dynamic material flow model at a global scale for the automotive system. They concluded that the continuation of the above mentioned strategies will result in a non-recyclable scrap surplus by around 2018 with an uncertainty margin of about 5 years.

The mixture and accumulation of alloying elements in the final scrap streams, especially those for which the removal from the melt is problematic, indicates that besides the amount of Al scrap also the composition must be taken into account in the environmental impact assessment at the material recycling phase.

3 METHODOLOGY

A major bottleneck in current LCA methods is that quality degradation during recycling cannot be properly addressed [11]. Most studies account the scrap flows and the produced secondary metals as equivalent in terms of quality, ignoring quality degradation. Recent studies highlight the role of quality and dilution losses during metal recycling, focusing on streams of ferrous materials [12] and aluminium [11]. In this paper the term quality is referring to purity or Al content of the stream and not to the physical properties.

For this purpose and in order to assess the environmental impact during aluminium recycling, an LCA based methodology has been developed. This approach takes into explicit account the interconnection between the quality of the resource inputs and the specifications of the alloy product focusing on the contamination by alloying elements during Al recycling. The environmental impact is used as a metric to express and quantify quality and dilution losses during metal recycling. The presented methodology can be used to evaluate the efficient use of resources during the secondary metal production. Figure 2 presents the system boundaries and functional unit of the LCA based analysis. Since the secondary production process aims at a specific aluminium alloy as output, the functional unit is set at 1 kg of the target aluminium alloy. In order to accurately quantify and assess the environmental impact of the production of the target alloy, the composition of the input scrap streams as well as the desired target alloy specifications (compositional tolerance limits according to the industrial standards [1]) need to be taken into account. Primary Al needed for dilution of the hard to refine alloying elements of the scrap mixture and required additions of all the typical alloying elements in order to adjust the alloy composition after dilution were included.

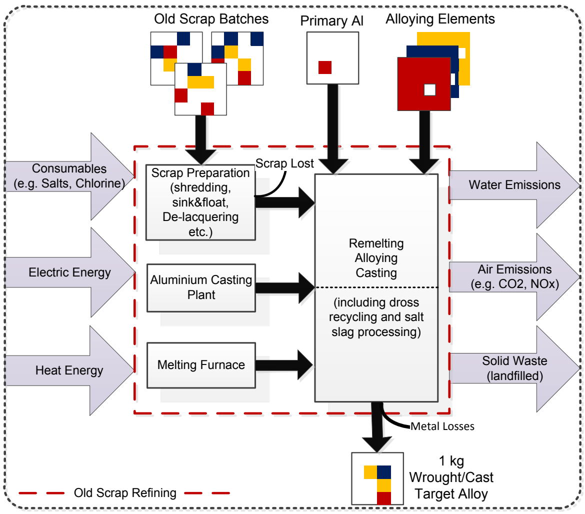


Figure 2: System boundary of the Al recycling process including melt refining and the functional unit.

The analysis is focusing on the four major alloying elements (Si, Fe, Cu and Mn) for Al that remains in the metal phase during remelting [2]. For these elements, the removal from the melt is very difficult or technically impossible, as explained in Section 2.1 and dilution is required to decrease their concentration in the melt. Mg was excluded; since it can be easily extracted from the melt (in the slag phase) at some appreciable extend by the widely industrially used salt fluxing and flotation/de-gassing refining technologies [5,6]. The environmental impact of these treatments along with the dross and salt slag recycling were included. The ReCiPe LCIA method (Endpoint Europe H/A) was used to calculate the environmental impact. The Eco-Invent v2.2 LCI datasets [13] and the latest environmental report from the European Aluminium Association (EAA) [14] were used to model the processes. The environmental impact is expressed in "ecopoints" Pts, (1000 mPts=1 Pts), where one point can be interpreted as one thousandth of the annual environmental load (damage) of one average European inhabitant.

Zinc is the major alloying element only for the 7XXX alloy series, and for the other series occurs in low concentrations. The influence of Zinc was considered to be negligible since: i) can be partially lost by evaporation in the gas phase, and ii) the 7XXX alloy series was not included in the case studies. From the EEA recycling model [14], it is estimated that 1108 kg of Al scrap enters the scrap preparation phase (consisting of unit processes like shredding, shink and float, de-lacquering) accompanied with approximately 211 kg of foreign materials. Afterwards, 1055kg of scrap exits the scrap preparation and enters the melting model for producing 1 tonne of ingot. Material losses which include the scrap preparation losses and the melting losses are also included.

4 CASE SELECTION

The investigated scrap streams are examined based on their expected mean compositional values from the literature and are considered to be discarded from: i) castings used in engines and transmissions from vehicles [8], ii) wrought products from automobiles with a rough separation between cast and wrought fraction [15], iii) wire and cable scrap [6], iv) used beverage cans (UBC) [6], v) buildings [9], vi) consumer durables [9], vii) from the major alloy series 6XXX excluding the two main alloys of this series AA6061 and AA6063 [9] and viii) a single alloy AA6061 [1]. To handle scrap composition uncertainties, the compositional window of the target alloys (maximum and minimum tolerance limits) for each element was narrowed by 5%. Al 99.7 (1070 AA similar alloy) is considered equivalent to primary Al, according to the chemical composition specifications of the London Metal Exchange for high grade aluminium contracts [16].

As target alloys in the case studies the following materials were used: AA3104, one of the largest volume alloys in the industry since it is used in the can body of beverage cans among other applications, and ii) 380.0, a typical die cast alloy used in automobile castings with high composition limits in alloy content.

A graphical representation of the mean/expected composition values of the scrap streams and of primary Al used as diluting agent, along with the target alloys' maximum composition tolerance limits, can be found in Figure 3. Each scrap batch was used as input, together with primary Al and alloy elements (assuming sufficient quantities), to examine: i) the maximum scrap utilisation of each scrap stream, ii) the normalised overall environmental impact per normalised kg and iii) the quality and dilution losses. The maximum scrap utilization rates of each scrap stream for the production of the selected target alloys is presented in Figure 3.

5 CONCLUSIONS

The environmental impact contributions per kg of the desired target alloys, representing the environmental optimum scenario of maximum scrap utilization and minimum material down-cycling for the desired alloy production, are shown in Figure 4. Based on the results the following major conclusions can be drawn:

- The engine and transmissions batch (cast alloys), having a high alloy content, cannot be utilised in large quantities to produce the target alloy AA3104. The low scrap utilization value (7.8%) in most cases is the reason why cast alloys cannot be recycled to anything else than casting quality. In contrast, when the target alloy is the AA380.0, specifically used for vehicles casting, the impact lowers significantly since no dilution is needed except for a small addition of alloy elements. The scrap usage in the latter case reaches 99.7%.

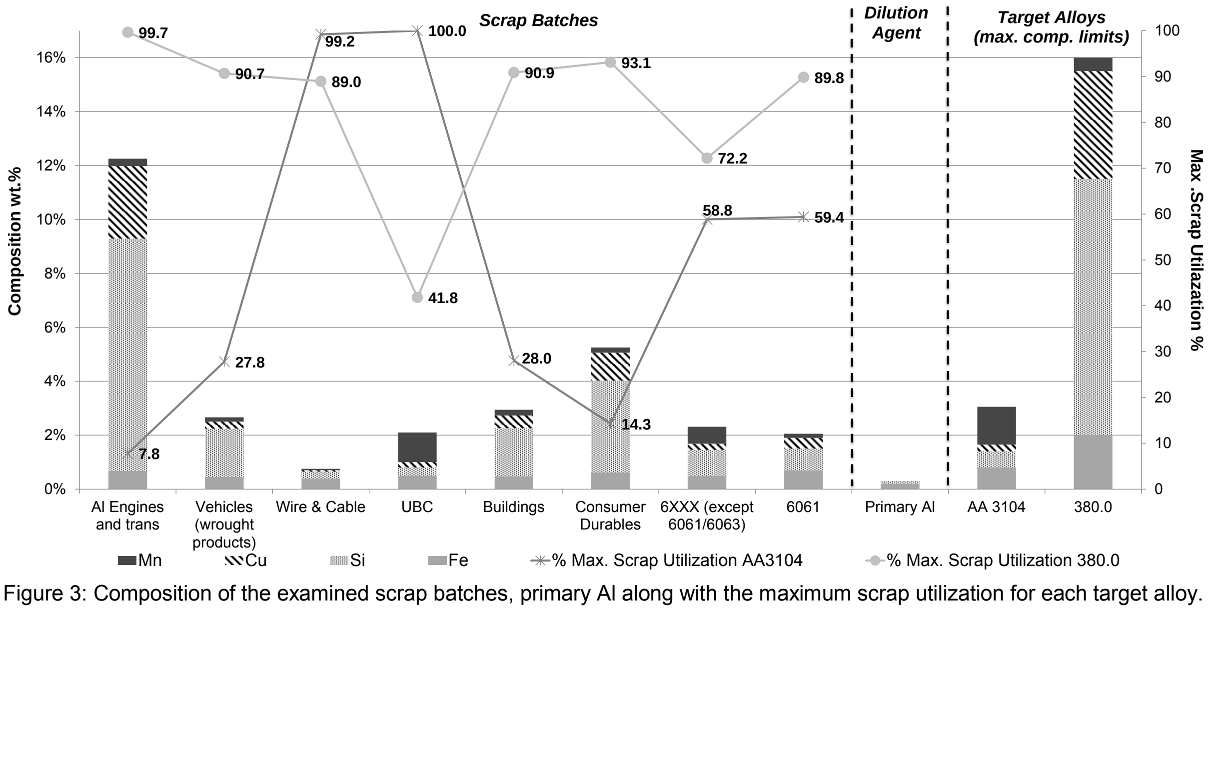


Figure 3: Composition of the examined scrap batches, primary Al along with the maximum scrap utilization for each target alloy.

- Preserving the quality of the scrap streams (UBC scrap to AA3104 or engine scrap to auto cast alloys) by utilizing it in compositionally closed recycling loops, can offer significant environmental benefits. UBC scrap can be fully utilised in the AA3104 alloy (used for the can tabs) without any addition of alloying elements and primary Al reaching the optimum 100% scrap usage. This strategy is already followed and represents an ideal example of an appropriate closed loop recycling based on separation of the scrap streams according to product applications. But this strategy is not always followed and can be expanded to other product systems, e.g. Al engine scrap to an alloy used for automotive castings.
- A ‘rough’ separation [15] between cast and wrought scrap in the End-Of-Life (EoL) treatment of vehicles can be environmentally beneficial. In particular, during the EoL treatment of vehicles, the engines are removed from the car in order to be depolluted. Thus, the biggest cast fraction in automobiles can easily be sorted separately and used in the auto cast production with higher scrap utilisation than wrought alloys, substituting the alloy elements addition with the alloy content. Hatayama et al. [9] illustrated that scrap sorting of ELV can significantly lower the future generation of un-recycled scrap and reduces the primary Al requirements by 15-25%. The separated wrought fraction can be used more efficiently for wrought alloys production, increasing the old scrap usage and decreasing the primary Al consumption.
- The scrap streams from: i) buildings and ii) wrought products from vehicles show a similar impact performance since they are characterised by only limited compositional differences. By selectively collecting them and utilizing them for wrought alloy production, higher substitution values for primary Al can be achieved.
- Depending on the desired target alloy, a suitable scrap input can be identified from environmental perspective. Moreover, it is possible to also identify how much scrap sorting is needed depending on the targeted alloy output. For the production of the AA3104 alloy, for example, the 6XXX and the 6061 alloys have similar maximum scrap utilisation. Thus, the sorting strategy in that case can target the 6XXX alloy family and additional sorting may not be required within this alloy series.

Quality and Dilution losses during recycling

A graphical representation of the overall environmental impact, combined with a breakdown analysis of the impact contributions, is shown in Figure 4. The overall environmental impact can be separated into four different contribution areas: i) the impact of the recycling process itself (mainly due to the energy consumption) and excluding the metal inputs ii) the scrap usage impact consisting of the scrap preparation and transportation to the plant, iii) the impact of the primary Al addition needed to dilute the contaminants, and iii) the impact of the alloying elements addition. The impact of the latter areas represents the dilution and quality losses respectively. Dilution of the impurities can be made also with high purity scrap inputs, but scrap blending scenarios will be examined in future work and was considered out of the scope in this analysis in order to examine each scrap stream separately. Dilution loss of the scrap mixture is expressed by the environmental impact originating from the primary Al addition and quality loss is reflected by the alloy elements addition. A graphical representation of these losses can be found in Figure 4, for the two representatives and at the same time contradictory case studies (wrought versus cast alloy).

For the production of the AA3104 alloy, most of the scrap batches need to be diluted and quality loss does not contribute significantly to the overall impact per kg. On the other hand, targeting the lower purity requirements of the 380.0 alloy, quality losses are visible highlighting the significance of material down-cycling during recycling.

Targeting the 380.0 alloy as output, none of the scrap batches, except for the UBC and the 6XXX, need dilution. The difference in scrap usage (from 99.7% for the engine and transmission scraps to the 89.0% scrap usage of the wire and cable scraps) is due to the alloying elements addition that can

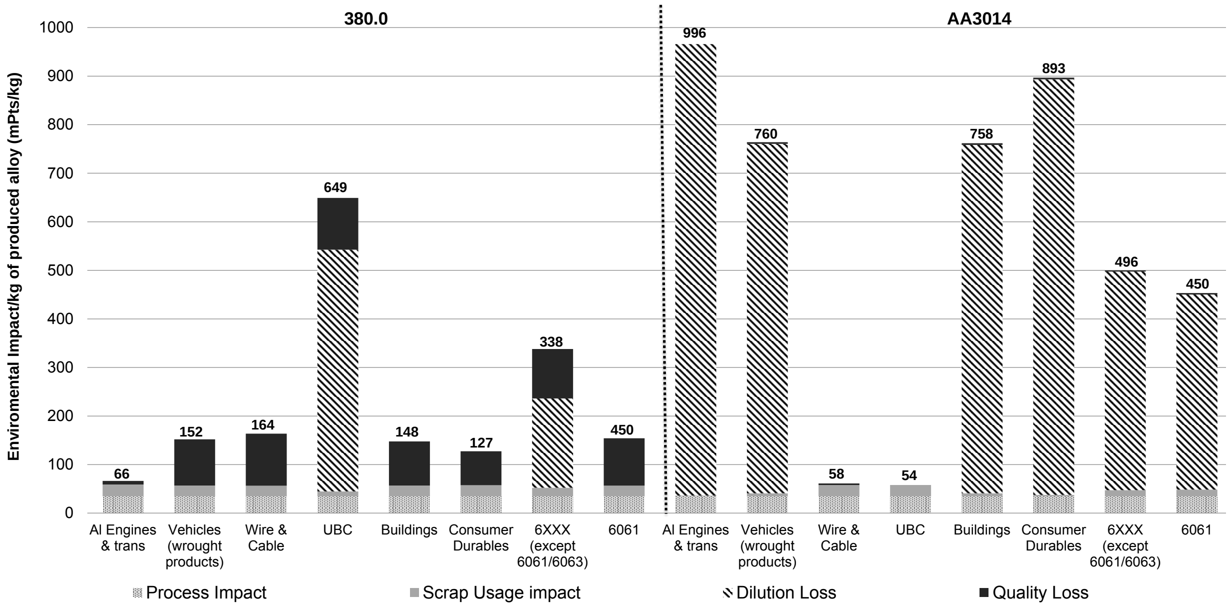


Figure 4: Overall environmental impact/kg (mPts/kg) along with the impact contributions for the production of the target alloys utilizing each scrap batch, primary Al and alloying elements.

significantly influence the overall environmental impact per kg of the produced alloy. Due to the higher quality losses, the wire and cable scrap batch shows a nearly 2.5 times higher environmental impact per kg (152 mPt/kg), compared to the engine and transmission scrap batch (66 mPt/kg). This example highlights the importance of minimising material down-cycling at production/product level.

Utilizing high purity and well defined scrap streams in wrought alloy production, the overall environmental impact can be significantly reduced by decoupling wrought production from primary Al at higher rates. Improving the sorting of post-consumer scrap, the wrought fraction can be increased, resulting in more efficient substitution of primary Al in the wrought alloy production. Moreover, since quality loss is an important impact contributor; the effort should be to substitute alloying elements addition with the scrap alloy content.

6 OUTLOOK

Since the removal of alloying element during remelting is very difficult or problematic for most of the elements, it is important to more efficiently control their concentration in the scrap streams before re-melting. Comparison of the environmental impact to process scraps metal back into different target alloys, is crucial to develop a sustainable scrap management strategy and identify compositional tighter recycling loops. In this respect the single alloy strategy is the best sorting approach since quality loss and the need for dilution are avoided. Utilizing high purity scrap streams for the production of wrought alloys, higher primary Al substitution rates can be achieved. Furthermore, lower purity scrap streams have a higher potential to substitute alloying element addition as require in cascade recycling.

Moving from open to compositionally ‘tighter’ recycling loops, finally resulting in single alloy recycling loops, will minimize the need for primary Al required for dilution and the need for alloying elements addition, resulting in large environmental and economic improvements at production and ultimately product level. Finally, a more different approach focusing on solid state / meltless recycling of aluminium scrap can provide significant environmental benefits, mainly by avoiding metal losses during remelting [17].

7 ACKNOWLEDGEMENTS

The authors acknowledge the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) through its PhD grant No. 091232 as well as the O&O EnHiPro project (Project No. 090999).

8 REFERENCES

[1] Davis JR. Chemical Compositions and International Designations for Aluminium Alloys In: Metals Handbook Desk Edition, 2nd edition, ASM International, 1998; p. 426-436.

[2] Nakajima K, Takeda O, Miki T, Matsubae K, Nakamura S, Nagasaka T. Thermodynamic analysis of contamination by alloying elements in aluminium recycling. Environmental Science Technology 2010; 44:5594–5600.

[3] Nakajima K, Takeda O, Miki T, Matsubae K, Nagasata T. Thermodynamic analysis for the controllability of elements in the recycling process of metals. Environmental Science Technology 2011; 45:4929–4936.

[4] Gaustad G, Olivetti E, Kirchain R. Improving aluminum recycling: A survey of sorting and impurity removal technologies. Resources, Conservation and Recycling 2012; 58:79-87.

[5] Reuter MA, Boin UMJ, van Schaik A, Verhoef E, Heiskanen K, Yang Y, Georgalli G. The metrics of material and metal ecology: harmonizing the resource, technology and environmental cycles. Elsevier Science, Amsterdam (2005) p. 706.

[6] European Committee for Standardization. EN 13920: Aluminium and Aluminium Alloy-Scrap, Part 1 to 16, 2003.

[7] ISRI- Institute of Scrap Recycling Industries Inc. Scrap Specifications Circular. 2013.

[8] Kirchain R, Cosquer A. Strategies for maintaining metal reuse: Insights from modeling of firm-wide raw materials availability and demand, Resources, Conservation and Recycling 2007; 51:367-396.

[9] Hatayama H, Daigo I, Matsuno Y, Adachi Y. Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology. Resources, Conservation and Recycling 2012; 66:8-14.

[10] Modaresi R, Müller DB. The Role of Automobiles for the Future of Aluminum Recycling. Environmental Science and Technology 2012; (16):8587-8594.

[11] Amini SH, Remmerswaal J, Castro MB, Reuter MA. Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis, Journal of Cleaner Production 2007; 15:907−913.

[12] Nakamura S, Kondo Y, Matsubae K, Nakajima K, Tasaki T, Nagasaka T. Quality and Dilution Losses in the recycling of ferrous materials from end-of-life passenger cars: input-output analysis under explicit consideration of scrap quality. Environmental Science Technology 2012; 46(17):9266-9273.

[13] Classen, M., Althaus, H.-J., Blaser, S., Doka, G., Jungbluth, N., Tuchschmid, M. 2009: Life Cycle Inventories of Metals, Final report ecoinvent data v2.1 No.10, Swiss Centre for LCI, Dübendorf, CH.

[14] EAA European Aluminium Association. Environmental Profile Report for the European Aluminium Industry: Life Cycle Inventory data for aluminum production and transformation processes in Europe, 2008.

[15] Hatayama H, Yamada H, Daigo I, Matsuno Y, Adachi Y. Dynamic Substance Flow Analysis and Its Alloying Elements. Materials Transactions 2007; 48(9): 2518-2524.

[16] LME London Metal Exchange, Special Contract Rules for High Grade Primary Aluminium 2010; available at: http://www.lme.com/downloads/metalsspecs/LME_Specifications_for_Primary_Aluminium_111010.pdf

[17] Paraskevas, D., Kellens, K., Renaldi, Dewulf, W., Duflou, J.R. (2012): Resource efficiency in manufacturing: Identifying low impact paths, 10th Global Conference on Sustainable Manufacturing (GCSM2012), Istanbul, pp. 271-276.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

10.2 Attractiveness criteria for remanufacturing in Brazilian enterprises

Barquet, A. P.[1], Guidat, T.[2]; Hamamoto, T.[1]; Rozenfeld, H.[1]; Seliger, G[2].

[1] Department Industrial Engineering, University of Sao Paulo, Sao Carlos, SP, Brazil

[2] Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany

Abstract

Brazilian industry has the challenge to maintain sustainable growth, considering economic, environmental and social dimensions. Remanufacturing, a strategy that aims to recover used products to "as new" quality and maintain its original product identity, can contribute to face this challenge. This paper's aim is to describe remanufacturing attractiveness criteria that could improve or contribute to the development of remanufacturing oriented business models. The attractiveness criteria cover laws, challenges and motivations influencing remanufacturing. They are defined based on literature research and on an analysis of industrial companies remanufacturing in Brazil. Results comprise the description of the main attractiveness criteria for a sample of 12 Brazilian industrial companies involved in remanufacturing as well as discussion about the influence of the Brazilian Law for Solid Waste on remanufacturing activities.

Keywords:

Attractiveness criteria, Brazilian industry, Business models, Remanufacturing

1. INTRODUCTION

United Nation's Millennium Development 7th Goal states that it is necessary to ensure environmental sustainability to allow poverty alleviation. Specifically, target 7d mentions that at least 100 million slum dwellers should see a significant improvement in their lives [1]. This statement confirms the validity of the three pillars of sustainability: considering on an equal priority economical, ecological and social dimensions of human activities. An essential solution for reaching this objective is to develop innovative and practical practices to allow decision makers in companies a progression in each of these three dimensions.

In the contemporary context of globalized market economy, the economical dimension is considered as the most important motivation factor for decision making in companies. Hence, cost reduction measures have been the cornerstone of manufacturing companies, motivating to apply minimal ecological and social considerations in the definition of their production processes. Therefore, the image of manufacturing is traditionally associated with environmental depreciation [2-3]. An evolution of production practices can bring an essential contribution to the vital aim of reaching sustainable global development standards [4], allowing a valid and responsible policy definition for both private and public institution [5] - dangerously lacking in numerous developing countries, including Brazil.

Characteristics of the Brazilian industrial sector

The Brazilian policy makers have been recently contributing to a better consideration of the sustainability dimensions. In 1998, the country enacted its first Environmental Crimes Law, inserted in the national penal law. This document also integrates a mandatory restoration of the damages caused. If Brazil is one of the few pioneering developing countries that enacted environmental public policies – alongside with South Africa, Namibia, Ecuador, Costa Rica, Vietnam and India – it is unique to embed the notion environmental restoration [6]. However, if compared to European legal environmental framework applied to manufacturing such as ROHS and WEEE legislations, Brazil environmental policy can be regarded as permissive or incomplete.

Remanufacturing as a potential enabler for sustainability

The private sector has potential to generate pathways to sustainability regarding their industrial activities. A sustainable production management has the potential to allow better access to goods to the poorest while opening new markets for company. An exemplar application is the concept of *circular economy*. The circular economy was defined for the first time in 1976 by Walter Stahel and Genevieve Reday as follows: the vision of an economy in loops (or circular economy) and its impact on job creation, economic competitiveness, resource savings, and waste prevention [7]. Beyond pure environmental concerns, the concepts has from its beginning focused on sketching "potential for substituting manpower to energy" through increasing economic competitiveness while achieving social development targets.

Some approaches are being considered by companies for defining recovering strategies for products that reaches their end of life (EOL) stage. Beside waste reduction, remanufacturing is the most promising strategy for enabling several product life cycles [8]. The EOL product, also named core, returns to the production process and pass thought steps like disassembly, cleaning, refurbishment, inspection and assembly, thus originating a product with the same quality and warranty as a new one. In addition, remanufacturing process preserves part of the raw materials and value added to the product during its fabrication, allowing companies to increase their productivity [9].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

Motivations to implement remanufacturing can be highlighted. Environmental and economic issues and market strategy are examples it [10]. By performing remanufacturing, companies can increase the degree of competitiveness, gain new customers as well as contribute toward more sustainable production and consumption, by being responsible for the management of EOL products [11-12].

Only few Brazilian companies are committed with the final destination of the used products they manufacture, although this situation is expected to change in the near future because of to the enacted National Policy on Solid Waste in 2010.

Potentials of the Brazilian remanufacturing industry

The potential of remanufacturing is still underexploited in many countries. Particularly in Brazil, remanufacturing is underdeveloped and its growth has been stimulated by discussions concerning the international trade of products [13]. Some of the difficulties found to implement remanufacturing are the lack of specific legislation [14-15] and the low credibility that some companies attribute to remanufacture, as many believe that this end of life strategy can have a negative effect on their main goal, which is the production and selling of new products [16]

Despite the motivations to remanufacture, the lack of exploration on remanufacturing is related to some challenges companies face to implement and manage a remanufacturing system [9]. These challenges are mainly related to reverse logistic activities [10], remanufacturing process [17-19], EOL product acquisition [20] and demand for remanufactured products [20-21].

This paper's aim is to describe remanufacturing attractiveness criteria that could improve or contribute to the development of remanufacturing oriented business models. The attractiveness criteria cover laws, challenges and motivations influencing remanufacturing in Brazilian. In addition, influence of the new Brazilian law (National Policy on Solid Waste) was evaluated to identify new motivation sources for remanufacturing. To reach this goal, a survey was created and answered by companies that are doing remanufacturing. The survey was created with the support of a literature review about remanufacturing challenges and motivations. Following, a detailed explanation of the methodology and description of the survey application can be found.

This research has been carried out in the context of the project “Networking of small and medium enterprises for competitive remanufacturing”, which is part of the BRAGECRIM Program - Brazilian and Germany Collaborative Research Initiative in Manufacturing.

2. METHODOLOGY

The methodology carried out contains three steps. First, a literature review was done to identify which are the challenges and motivations of remanufacture.

These challenges and motivations were then used to create a questionnaire for application in a survey. After the identification from the company profile; a first section relates to the main motivations for remanufacturing. The second section concerns the challenges. Answer options for these two questions were the data acquired by literature research, which are described on section 3. Questions about the company profile, such as activity sector, position in the value chain and company size also composed the survey questionnaire.

The third step is the administration of the questionnaire through a survey. Thanks to the existing collaboration within CNI/SENAI, it was possible to participate to the FIMAI Fair (Feira do Meio Ambiente Industrial e Sustentabilidade – Fair for Environmental Management and Sustainability Industry), a major industrial fair for the environmental management industry in Brazil that took place in Sao Paulo in August 2012.

The questionnaire has been exclusively administrated by means of personal interviews with sales or technical manager available in the fair. Interviewers were informed about the research background and concepts of the main topics of the research prior to the administration of the survey.

3. REMANUFACTURING CHALLENGES AND MOTIVATIONS

3.1. Remanufacturing Challenges

The acknowledgement about remanufacturing challenges can support companies of increasing remanufacturing effectiveness, since they can explore the main problem sources and develop solutions to face them adequately.

The most common challenges identified during literature review are: reverse logistics costs, complexity and costs of remanufacturing processes, difficult on acquiring cores, low demand for remanufactured products and competition for acquiring core. Their descriptions are presented below.

Reverse logistics (RL) costs

Challenges related to reverse logistics are mentioned by Kato and Laurindo [10]. The author addresses that difficulty in predicting volumes, return times, and quality conditions of EOL product hampers the planning of the remanufacturing operation.

The costs related to reverse logistics activities can increase because of some challenges such as: difficulty to control EOL products' flow to be remanufactured and thus to measure its remanufacturing potential before they enter into the reserve flow [17,20,23]. In addition, the great variety and spread of EOL products that can be collected hamper economy of scale potentials for remanufacturing activities [19].

Remanufacturing process complexity

The remanufacturing process is also considered complex and costly for many companies, mainly because of the complexity of process steps. There is little precision on inspection step and difficulties are addressed to execute this step [17,19]. Cleaning step is considered complex since there is a variety of cleaning agent and the choice of one will dependent on the EOL product to be remanufactured [12,24]. Also, the cost of remanufacturing process is assigned to the low automation of the process [18].

Core acquisition

Another challenge to remanufacturing companies is the difficulty on acquiring EOL products, the raw material for remanufacturing process. A lack of collaboration in the relationship between the remanufacturer and his supplier is considered one of the main causes for this challenge [20].

Demand for remanufactured products

Many customers believe a remanufactured product is a second hand or low quality product because it contains parts that previously composed other products. This leads to a low acceptance of remanufactured products [21] and thus to a low market demand [17,22,25]. Uncertainty of the quality of these products increases customer distrust to buy them [25,26].

Competition for cores

Another problem is that other companies, known as independent or third-part remanufacturing companies, compete with EOL product. They acquire them and recondition some parts and label it as remanufactured goods. This fact leads to two problems. First, the commercialization of low quality products which increases the belief that remanufactured products has low quality. Second, a smaller quantity of cores will be available for OEM (Original Equipment Manufacturer) to execute remanufacturing [27].

Challenges for remanufacturing	
Reverse logistics costs	- Prediction of quality, quantity and moment when products can return - Product variety and geographical spared
Remanufacturing process complexity	- Low precision of cores inspection - Setting of the cores inspection - Cleaning agent choice - Low level of process automation
Core acquisition	- Lack of relationship between remanufacturer and core supplier
Demand for remanufactured products	- Low acceptance from customers - Low market demand - Variable product quality
Competition for cores	- Low product quality - Low quantity of cores available for OEM

Table 1: Overview of main challenges for remanufacturing in the literature

3.2. Remanufacturing Motivations

Companies usually have motivations when deciding to implement new processes and systems. Sundin states that the motivations for companies to remanufacture are environmental issues, pressure of laws and market demand [17]. Amezquita, like Nasr and Thurston added financial motivations on remanufacturing decision [12,28]. Ijomah agreed with the four motivations described above [21].

Motivations for the OEM to remanufacture are also presented by Toffel [25]. These motivations are decrease of costs and resources on production processes, reinforce and protect the branch image and protect the market share. USA and Europe have differs when it comes to their main motivation to remanufacture. In USA, the interest on remanufacture is growing because of its profitability potential. In Europe, laws pressure is the main motivator [30].

Market demand

The research of Lindahl, Sundin and Östlin [31] concludes, according to literature review and case studies, that remanufacturing is preferable compared to the manufacturing of new products since it requires less resources which is economically advantageous for companies. For Giuntini and Gaudette [9], remanufacturing cost can be 40-65% smaller when compared to the manufacturing of new products. In addition, these authors affirm that the price of a remanufactured product can be 30-40% less than the price of a new product, which creates a demand for the remanufactured ones, since the quality and warranty of it need to be equal as a new one. Thus, the smaller price of the remanufactured products is considered one of the main motivations to execute remanufacturing [12]

Legislation

The great amount of waste generated by manufacturing processes is leading to the creation of laws that forces companies to reduce the environmental impacts of their products and processes [21]. Therefore, OEM is establishing ways to return and remanufacture EOL to comply these laws [32].

Environmental impacts (EI) reduction

As mentioned, remanufacturing process can lead to the decrease of resources regarding raw material extracted and energy consumed during the process [12].

Ayres, Ferrer and Van Leynseele [33] agreed with Amezquita et al [12] about the two main environmental effects of remanufacturing. The first is on the production process as the remanufacturing process uses EOL products and parts instead of raw material. The second effect is related to resources conservation, since remanufacture offers an alternative for EOL products, which can reduces the amount of waste generated.

Motivations for remanufacturing	
Market demand	- Potential for higher profitability than new production - Cost effectiveness - Reach of new markets
Legislation	- Waste reduction - Law compliance
Environmental impacts reduction	- Lower need for raw materials - Resources conservation

Table 2: Overview of main motivations for remanufacturing in the literature

4. SURVEY APPLICATION AND RESULTS

4.1. Description of the companies' sample interviewed

First section of the questionnaire aims at defining the basic profile of the company interviewed. The information requested on this matter can be classified according to the following categories: activity sector, position in the value added chain and size in terms of number of employees currently working in the company.

Respondents' sample

Out of the 46 respondents to the survey, 14 companies informed that they already identified one product within their portfolio that has potential to be remanufactured. Out of the 14 companies, 12 provided information concerning the motivations and the challenges for remanufacturing. This is the sample selected for this paper.

Activity sector

The question concerning the activity sector has been formulated with closed categorical options with unique answer possibility. It contains activity categories customized to the companies taking part to the FIMAI fair. Possible answers are automotive, industrial machinery, consumer electronics, electronic equipment, personal goods, defense and aeronautics, packaging, chemical products, pharmaceutical products and medical equipment. In case the companies have activities in more than one activity sector, it was required to mention the most significant activity only. Figure 1 gives a graphical representation of the answers obtained.

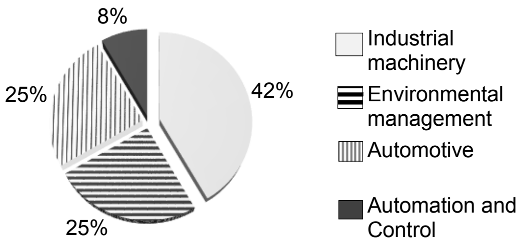


Figure 1: Answers description for the activity sector

Position in the value added chain

An important aspect of the sample description is the position of the company within its value added chain. The question presents closed categorical options and allows multiple answers. It has been designed according to simplified description of the potential actor's role within the remanufacturing operations' process. Possible answers are Original Equipment Manufacturer (OEM), distributor, parts or component supplier and reverse logistics (including every post-EOL operations). Figure 2 shows the percentage of positive answers from respondents on the base of the maximal possible answers. This representation is chosen to represent the multiple answer nature of the question.

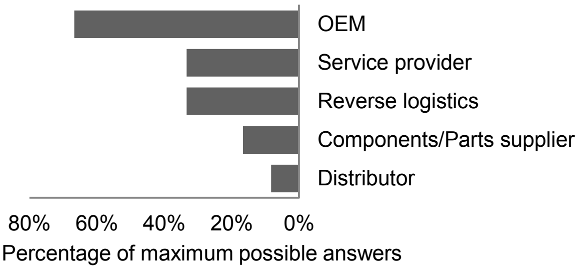


Figure 2: Company sample profile according to its position on the value chain

Company size by number of employees

Another element of appreciation for the company profile is the number of employees currently under contract. This question was closed and offered ranges as answer options. The ranges were defined according to IBGE (Instituto Brasileiro de Geografia e Estatística). Figure 3 represents the distribution of respondents for this question.

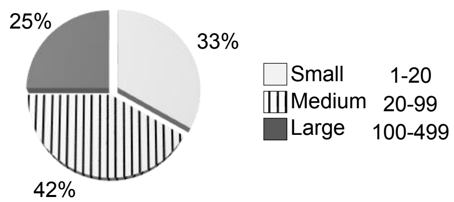


Figure 3: Answers description for the company size

4.2. Results for Remanufacturing Challenges

It can be noticed that no new challenge has been added and also that there is a homogeneity on the answers. Figure 4 indicates that most of the challenges companies' faces are related to the remanufacturing process itself. Cost and complexity of this process sum 53% of the challenges reported by companies.

Some practices can help companies in minimizing these challenges. First, abilities, knowledge and knowhow of employees working on remanufacturing process are essential to achieve an efficient process [34-36].

Another suggestion is to execute the remanufacturing process using the same facilities than the manufacturing process, in case when OEM remanufactures. It could facilitate the dissemination of knowledge between the employees evolved in both process and the knowledge transfer between the two processes, since manufacturing is more understood and structure than remanufacturing [29]

A third orientation is regarding how products are designed. Complexity and even costs of remanufacturing process can be higher if the product has a low level of remanufacturability, which means that it was not designed to be remanufactured on its end of life. That is why Design for Remanufacturing must be included into product development [9,19,21,22,37]

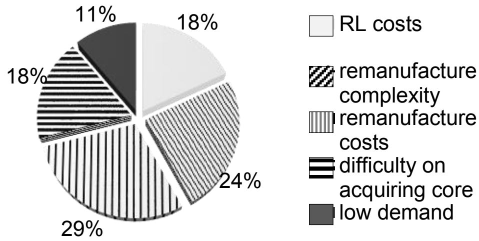


Figure 4: Challenges for remanufacturing mentioned by the company sample

4.3. Result for Remanufacturing Motivations

There is heterogeneity on the motivations companies have to do remanufacturing. As shown in figure 5, 41% indicated doing remanufacturing aiming to reduce environmental impacts (EI). This shows an increase of environmental conscious both for companies concerned by decreasing the environmental impacts of their products and processes, and clients demanding more environmentally-friendly products.

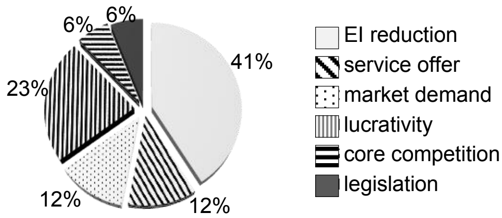


Figure 5: Motivation for remanufacturing mentioned by the company sample

A new motivation was reported from respondents: the opportunity to increase services offering and customer satisfaction. This fact suggests that companies are increasing services offer, which goes in the same direction as researches that shows the increase of manufacturing companies integrating service on their products by means of Product-Service Systems (PSS). These researches consider remanufacturing and PSS as synergistic approaches for reaching the sustainability dimensions [36,38,39].

Two of the motivations reported on the literature review were not selected as expected by companies: legislation and competition for the core. The low selection of the competition for core option is quite unexpected since most of the sample is OEMs. As a new legislation had been approved in Brazil, a specific question about the influence of this law on remanufacturing decision was inserted on the questionnaire. Next item shows the answers for this question.

4.4. Law as a motivation or a challenge?

A question about the new Brazilian law was inserting on the questionnaire. Aim is to evaluate if the new Brazilian law, named National Policy of Solid Waste [40], is influencing the remanufacturing activities of the investigated companies. The answers percentages are shown of Figure 6.

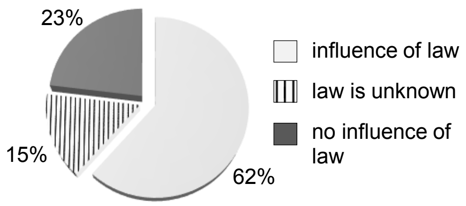


Figure 6: Influence of the Brazilian law on solid waste mentioned by the company sample

According to the companies participating on the survey, 62% of them believe the Brazilian law is influencing their remanufacturing activities. Despite of that, just 12% of them consider laws as a motivation to remanufacture. This could indicate some statements. First, despite companies are been influenced by the law, they don´t consider it as a motivation. Second, as the law was approved in 2010, some companies still didn´t realize it as a motivation. Third, there is a lack of guidelines to support companies on developing concrete actions to be complying this law. Guidelines could hasten the reduction of environmental impacts caused by industries and also works as motivation not only for remanufacturing but also for the implementation of other end-of-life strategies, such as recycling and repairing.

5. DISCUSSIONS

According to the most frequent patterns, some considerations can be outlined aiming to provide solutions and improve the business model of remanufacturing enterprises. Thus, considering the challenges reported in thus research and the current vision of Brazilian remanufacturing companies about the National Policy of Solid Waste, some suggestions were developed. They are:

- Develop solutions for remanufacturing process aiming to increase knowledge and efficiency and decrease costs and complexity;
- Include Design for Remanufacturing in Product Development Process;
- Increase the service offer and provide PSS and remanufacturing as synergic approaches;
- Create guidelines to support Brazilian companies on complying National Policy of Solid Waste.

This paper discussed about challenges and motivations for remanufacturing, including the influence of a specific Brazilian law on remanufacturing activities. By means of 12 remanufacturing companies, some highlighted were presented.

Regarding remanufacturing challenges, the results showed that there was relevant challenges indicated by the companies since the percentage of answers for the different challenges was homogeneous. In respect to the motivations, one of them appeared to be most significant, at least for this set of companies. The concern on decrease environmental impact is considered the main motivation of the companies. Also, a motivation that was not included on the survey answers was indicated by the respondents. Companies are been motivated to do remanufacturing as a way to provide a service to the customer and thus increase the value offered and delivered to them.

Concerning Brazilian law, it was possible to realize that despite companies know and is influenced by this law; they do not consider it a motivation to remanufacture.

Therefore, considering the answers of the sample and highlights from literature, four suggestions to improve the business model of remanufacturing enterprises were deployed. However, this is a first attempt to support Brazilian remanufacturing enterprises and these suggestions must be detailed in concrete actions and activities in future studies.

A limitation of this research is the reduced number of companies' sample. However, this questionnaire had been improved and currently another survey are been carry out which intend to reach a bigger sample and thus allow qualitative analysis. By the end of 2013, the research team expected to have more confident results for future researches to support the improvement of remanufacturing in Brazilian companies and further in development and emergent countries.

6. REFERENCES

[1] http://www.un.org/millenniumgoals/environ.shtml. Last consulted on May 6th, 2013.

[2] Meadows, D.H et al., The Limits of Growth. A report for the Club of Rome's project on the predicament of mankind, Earth Island, London, 1972.

[3] Frosch, R. and Gallopoulos, N., 1989, Strategies in Manufacturing, Scientific American, vol. 261, no. 3, pp. 144-152.

[4] Seliger, G., 2012, Sustainable Manufacturing for Global Value Creation, in "Sustainable Manufacturing: Shaping Global Value Creation", Springer-Verlag Berlin Heidelberg, pp. 3-8.

[5] Pokrovskaia, N. N., 2012, Global and Local Regulating Approach for Sustainable Development, in "Sustainable Manufacturing: Shaping Global Value Creation", Springer-Verlag Berlin Heidelberg, pp. 287-292.

[6] Aronson, J., Brancalion, P. H. S., Durigan, G., et al., 2011, What Role Should Government Regulation Play in Ecological Restoration? Ongoing Debate in São Paulo State, Brazil. Restoration Ecology, 19: 690–695

[7] Stahel, W.R. and Reday, G., 1976, the potential for substituting manpower for energy, report to the Commission of the European Communities, Brussels.

[8] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and

repealing certain Directives (75/439/EEC, 91/689/EEC and 2006/12/EC)

[9] Giuntini, R., Gaudette, K., 2003, Remanufacturing: the next great opportunity for boosting US productivity, Bus Horiz, 46/6: 41-48

[10] Kato, P., Laurindo, F.J.B., 2004, Discutindo o Planejamento Integrado de uma Remanufatura em um ciclo fechado de Supply Chain, Proceeding of XXIV ENEGEP (Encontro Nacional de Engenharia de Produção), Florianópolis, SC (In Portuguese).

[11] Barquet, A.P., Rozenfeld, H., Forcellini, F.A., 2013, An integrated approach to remanufacturing: model of a remanufacturing system, Journal of Remanufacturing, 3: 1–11.

[12] Amezquita, T., Hammond, R., Salazar, M., Bras, B., 1995, Characterizing the remanufacturability of engineering systems, Proceedings of ASME Advances in Design Automation Conference. Boston, Massachusetts.

[13] Saavedra, Y.M.B., Barquet, A.P.B., Rozenfeld, H., Forcellini, F.A., Ometto, A.R., 2013, Remanufacturing in Brazil: case studies on the automotive sector, Journal of Cleaner Production, In Press.

[14] Oiko, O.T., Barquet, A.P.B., Ometto, A., 2011, Business issues in remanufacturing: two Brazilian cases in automotive industry, Proceedings of CIRP: 18th International Conference on Life Cycle Engineering, Braunschweig, Germany.

[15] Zanette, E.T, 2008, Remanufacturing in Brazil and Worldwide: Concepts and Conditions, University of São Paulo. Monography (in Portuguese).

[16] Saavedra, Y.M.B., 2010, Practices of End of Life Strategies with Focus in the Product Development Process and Applications to Companies that Perform the Recovery of Post-consumer Products, University of São Paulo, Master thesis (In Portuguese).

[17] Sundin, E., 2004, Product and process design for successful remanufacturing, Linkoping University, Dissertation.

[18] Gray, C., Charter, M., 2006, Remanufacturing and Product Design: Designing of the 7th Generation, The Centre for Sustainable Design, South East England Development Agency (SEDA).

[19] Ferrer, G., Whybark, D.C., 2000, From garbage to goods: successful remanufacturing systems and skills, Business Horizons, 43/6: 55-64.

[20] Jacobsson, N., 2000, Emerging product strategies: selling services of remanufactured products. Lund University, Dissertation.

[21] Ijomah, W.L., McMahon, C.A., Hammond, G.P., Newman, S.T., 2007, Development of design for remanufacturing guidelines to support sustainable manufacturing, Robot Comput Integrated Manuf, 23/6:712-719.

[22] Geyer, R., Jackson, T., 2004, Supply Loops and Their Constraints: The Industrial Ecology of Recycling and Reuse, California Management Review, 46/2: 55-73.

[23] Rogers, D.S., Tibben-Lembke, R.S., 1998, Going Backwards: Reverse Logistics Practices and Trends, Reverse Logistics Executive Council, Reno, Nevada.

[24] Steinhilper, I.R., Brent, A., 2003, Saving Product Lives in Global and Local Remanufacturing Networks: A Scientific and Commercial Work Report and an Outlook, Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan.

[25] Barker, S., King, A., 2007, Organising Reuse: Managing the Process of Design For Remanufacture (DFR), Annals of POMS 18th Annual Conference Dallas, Texas, EUA.

[26] Östlin, J., Sundin, E., Björkman, M., 2008, Importance of closed-loop supply chain relationships for product remanufacturing, Int J Prod Econ, 115:336-348.

[27] Ferguson, M. E., Toktay, L. B., 2004, The Effect of Competition on Recovery Strategies, Technology and Operations Management, INSEAD.

[28] Nasr, N., Thurston, M., 2006, Remanufacturing: A Key Enabler to Sustainable Product Systems, Proceedings of LCE: 13th CIRP International Conference on Life Cycle Engineering, Belgium.

[29] Toffel, M.W., 2004, Strategic Management of Product Recovery, California management review, 46/2: 120-141.

[30] Guide, V.D.R. Jr., Harrison, T.P., Van Wassenhove, L.N., 2003, The challenge of closed-loop supply chains, Interfaces, 33/6: 3-6.

[31] Lindahl, M., Sundin, E., Östlin, J., 2006, Environmental issues within the remanufacturing industry, Proceedings of LCE: 13th CIRP International Conference on Life Cycle Engineering, Belgium

[32] Seitz, M.S., 2006, A critical assessment of motives for product recovery: the case of engine remanufacturing, J Clean Prod, 15:1147-1157.

[33] Ayres, R.U., Ferrer, G., Van Leynseele, T., 1997, Eco-efficiency, asset recovery and remanufacturing, Eur. Manag. Journal., 15/5: 557–574.

[34] Ferrer, G., 2003, Yield information and supplier responsiveness in remanufacturing operations, Eur J Oper Res, 149:540-556.

[35] Hermansson, H., Sundin, E., 2005, Managing the remanufacturing organization for an optimal product life cycle, Proceedings of the fourth international symposium on environmentally conscious design and inverse manufacturing, Tokyo, Edited by Yamamoto R. IEEE, New York, 143-156.

[36] Sundin, E., Bras, B., 2005, Making functional sales environmentally and economically beneficial through product remanufacturing. Journal of Cleaner Production, 13/9: 913–925.

[37] Gallo, M., Romano, E. and Santillo, L.C., 2012, A Perspective on Remanufacturing Business : Issues and Opportunities. In International Trade from Economic and Policy Perspective. 209–233.

[38] Kerr, W., Ryan, C., 2001, Eco-efficiency gains from remanufacturing A case study of photocopier remanufacturing at Fuji Xerox Australia, Journal of Cleaner Production, 9: 75–81

[39] Mont, O., Dalhammar, C., Jacobsson, N., 2006, A new business model for baby prams based on leasing and product remanufacturing, Journal of Cleaner Production, 14/17: 1509–1518.

[40] National Solid Waste Policy (Politica Nacional de Residuos Solidos – Lei No, National Solid Waste Policy (Politica Nacional de Residuos Solidos – Lei No. 12.305/2010). Presidência da Republica. Brasil. (in Portuguese).

10.3 Considering real end-of-life scenarios in a design for disassembly methodology

N. Alonso Movilla [1], P. Zwolinski [1], F. Barnabé [2], C. Dalla Zuanna [2], V. Moulin [2]
[1] G-SCOP laboratory, University of Grenoble, France
[2] CETIM, Saint-Etienne, France

Abstract
Disposal of products is one of the main causes of pollution and resource depletion. Therefore, handling products at the end of their lifecycle is a matter of great importance since it aims to encourage different End-of-Life (EoL) strategies as recycling, remanufacturing and reuse. This research attempts to propose a methodology that integrates real EoL scenarios throughout the design process, focusing on the Design for Disassembly approach. The methodology consists of two major steps: first, an evaluation of assemblies and disassemblies is made; and second, three different recovery rates are established. It allows designers to explore different assembly alternatives in order to find the one that leads the highest percentage of components that can have a closed-loop lifecycle. A case study was carried out with a leading manufacturer of air conditioning systems to illustrate the proposed methodology.
Keywords:
Design for Disassembly; Ecodesign; End-of-Life; Recyclability Rate.

1 INTRODUCTION

In recent years, the European Union (EU) has issued directives that stipulate minimum recovery rates for a wide range of products [1], [2]. However, it is difficult to respect these recovery rates if products have not been designed taking into account their End-of-Life (EoL).

The aim of this research is to propose a methodology that integrates EoL properties throughout the design process, focusing on the Design for Disassembly (DfD) approach and on the calculation of recovery rates. Disassembly can be defined as a systematic method for separating a product into its constituent parts, components or other groupings [3]. In most recovery strategies (EoL scenarios, arrows 2 and 3, figure 1) it is necessary to disassemble the product fully or partially so every component can be treated in its respective EoL scenario [4]. Moreover, product disassemblability is highly correlated with product life cycle cost [5].

The methodology proposed in this paper is a practical and realistic disassembly method which enhances product recovery. Products with high recovery rates aim to lead to a more sustainable production. The optimization of the disassembly process is based on the quick separation of parts; hence, designers have to be able to easily identify the parts that are going to be disassembled at the end of the use phase. Therefore, the approach developed in this work considers real EoL scenarios in order to facilitate decision-making concerning the disassemblability of a product.

The outline of this study is as follows: Section 2 presents a review of the literature related to product disassembly assessment and Design for EoL. Section 3 proposes a methodology which consists of the assembly and disassembly evaluation and on the estimation of three recovery rates. Section 4 presents a case study, in which the method is applied to an existing product to validate the proposed approach. Finally, Section 5 summarizes the content of this paper and provides conclusions.

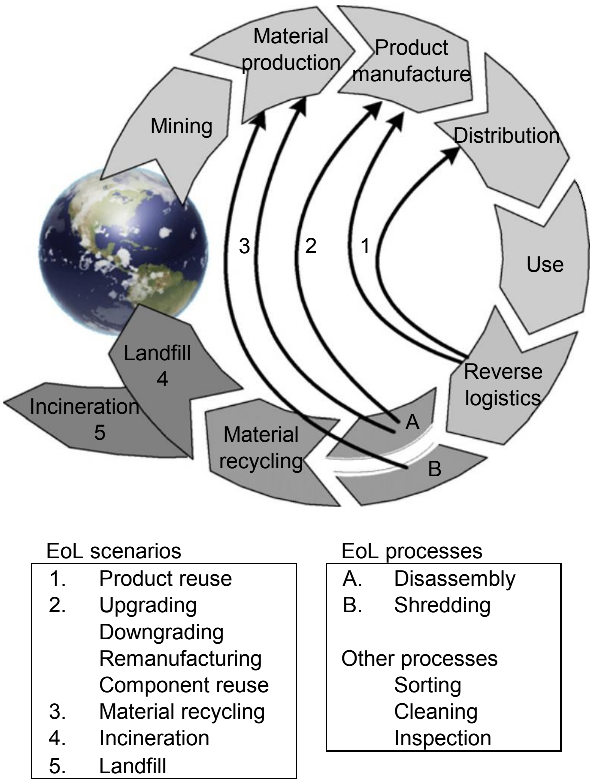


Figure 1: Product life cycle with the most important EoL scenarios and related processes, modified from Duflou *et al.* [6].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

2 LITERATURE REVIEW

DfD is a concept that can be treated from different points of view. It is related to other design concepts such as Design for Maintenance, Design for Recycling or Design for Remanufacturing. Numerous methods have been developed in the literature over the past two decades. Some of them focus on product disassembly assessment, whereas others focus on the optimisation of product EoL strategies. These methods are examined in this section.

2.1 Design for End-of-Life

Several tools and methods can be found in the literature on optimising product EoL strategies. As indicated in figure 1, products (or components) can follow different routes when arriving at their EoL. As shown in figure 2, reuse is the best EoL scenario in terms of material and energy efficiency. If products cannot be reused, they can be remanufactured. Remanufacturing is an industrial process whereby used/broken-down products are restored to a new life [7]. Material recycling is characterised by the reprocessing of materials both from residues of manufacturing processes and from materials used in products [6]. Energy recovery refers to the use of combustible waste as a means of generating energy through direct incineration with recovery of the heat [1]. The last consideration is waste disposal, which comprises incineration without energy recovery and landfilling [8].

The work of Favi *et al.* [9] describes an approach to support disassemblability evaluation. 6 indices are proposed to evaluate and measure the feasibility of the different EoL scenarios; *reuse index*, *remanufacturing index*, *recycle index*, *incineration index*, *landfill index* and *different treatment index*. Their method allows quantitative analysis of the effort for component disassembly based on cost.

Huang *et al.* [10] developed a method that aims to identify the ideal product disassembly pattern. For this, the authors considered the relationships between product components and represented them in a matrix. The purpose of their approach is to enhance design for 3R (reduce, reuse, recycle). Therefore, the strength of reducibility, reusability and recyclability between components is calculated.

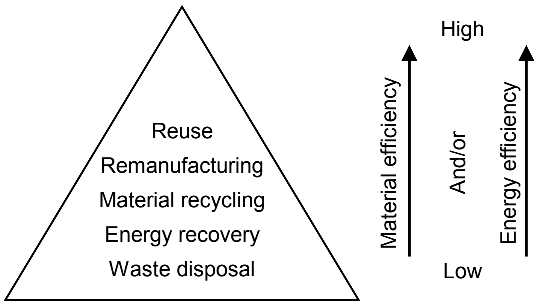


Figure 2: Theoretical recovery hierarchy, modified from Gerrard *et al.* [11].

Tchertchian *et al.* [12] proposed a methodology that aims to group modules from an EoL point of view. Remanufacturable and recyclable modules are characterised according to their environmental and economic properties. Different modules are grouped by calculating their affinity according to the criteria of reliability, obsolescence and range.

2.2 Disassembly assessment

Product assembly and disassembly evaluation is carried out within the approach presented in this paper. Different ways of assess the liaisons of a product can be found in literature.

Kroll *et al.* [13] presented a method for assessing the ease of disassembly of a product. Their approach is centred on a disassembly evaluation chart, in which every disassembly task is evaluated according to five categories of task performance: *accessibility*, *positioning*, *force*, *base time* and *special*. Once completed, the disassembly design effectiveness and the disassembly time can be calculated.

Along the same lines, Das *et al.* [14] presented a multi-factor model which aims to calculate disassembly effort index scores. Seven factors are evaluated to analyse product, part and material handling: *time*, *tools*, *fixture*, *access*, *instruct*, *hazard* and *force*. Following this assessment an estimate of disassembly cost can be made.

Assembly method	
A_1	Nail
A_2	Rivet
A_3	Screw
A_4	Retaining ring
A_5	Staple
A_6	Nuts and bolts
A_7	Push on fastener
A_8	Spring toggle
A_9	Zipper and Velcro
A_{10}	Cantilevered snapfit
A_{11}	Seam
A_{12}	Glue
A_{13}	Tape
A_{14}	Soldering

Disassembly process		Rating	
D_1	Self-removal of a part	Very Easy	Hands
D_2	Axial part pull out		
D_3	Levered removal		
D_4	Hammered removal	Easy	
D_5	Unscrewed out		
D_6	Shearing cut	Medium	Tools
D_7	Saw cutting		
D_8	Adhesive separation		
D_9	Crushing and bending	Difficult	
D_{10}	Drilling		
D_{11}	Flame cutting		
D_{12}	Soldering breakage		
D_{13}	Shredding	Very Difficult	Machines
D_{14}	Chemical dissolution		
D_{15}	Suction and drainage		

Figure 3: Determination of disassembly rate based on assembly relationships, by Kuo [15].

Yi *et al.* [16] proposed a method for disassembly time evaluation considering the type, size, weight, connection parts and the movement distance of a product. A base time is calculated considering 12 factors of influence that are classified in one of the following categories: *preparation time*, *movement time*, *disassembly time* and *post-processing time*.

Askiner [17] provided an analytic network process that aims to evaluate connection types. The connectors evaluated follow the same classification suggested by Sonnenberg [18], which are: *discrete fasteners*, *integral attachments*, *adhesive bonding*, *energy bonding* and *others*. The model presented evaluates the alternative connectors taking into account the manufacturing, in-use and EoL phases of the product lifecycle. Thus, for each of the phases different concerns are considered.

Kuo [15] developed a method based on petri net analysis to determine the optimal compromise between the cost and environmental efficiency of disassembly processes. In this methodology a disassembly index is determined based on assembly methods (figure 3). Difficulties in disassembly are measured depending on the tools used. Therefore, disassembly indices go from *very easy*, *easy*, *medium*, *difficul*t and *very difficult*.

Duflou *et al.* [6] reviewed current disassembly practices in order to identify factors influencing disassembly feasibility. According to them, a classification of the different tooling systems used in disassembly operations can be made based on the degree of operator involvement, resulting in the following classification: *manual operations*, *partially automated operations* and *fully automated operations*.

3 PRESENTATION OF THE DFD APPROACH CONSIDERING REAL EOL SCENARIOS

3.1 Brief description of the methodology

Disassembly and recycling analyses are inevitably confronted when dealing with the issue of EoL products' treatment [19], [20]. The quantitative ecodesign tool presented in this paper allows designers to take into account disassembly and recycling concerns during the detailed design stage. It aims at enhancing product recovery by analysing components' real EoL scenarios and by suggesting new assemblies' alternatives.

3.2 The 6 steps of the methodology

The methodology comprises 6 steps that are described in the following paragraphs.

Step 1: Identification of product components and assemblies

First, information concerning product components or subassemblies (materials, mass) and their assembly relationships and technologies are obtained from the bill of materials (BOM) and the CAD model.

Step 2: Identification of target components

In this phase components that must be dismantled at the end of the product's life for safety, regulatory or recovery reasons (*target components*) are identified and classified in one of the following EoL scenario categories:

- Reuse/Remanufacturing: Parts that must be removed for reuse or remanufacturing in a nondestructive way so that their functional value is preserved.
- Recycling: Parts that must be removed for material recycling. The functional value of the part is not preserved so it can be destructively disassembled.
- Depollution: Parts that must be removed for selective treatment because of safety reasons and/or regulatory constraints.

Step 3: Determination of disassembly precedencies

During this stage physical precedencies among components are set up in a disassembly precedence table. A disassembly tree can be represented using this information. Thereby it allows designers to know which components are directly accessible and therefore directly disassembled. This information is required to do the subsequent disassembly evaluation (stage 4).

Step 4: Assembly and disassembly assessment

The fourth phase is the assessment phase in which target components are evaluated following the assembly and disassembly criteria shown in table 1. The criteria take values to a range from 0 to 1. A liaison index is computed to measure the capacity of a component to be assembled and dismantled. The liaison index is the average of both the assembly and disassembly criteria, as presented in the following equation (1):

Table 1: Assembly and disassembly criteria for target components' evaluation.

Assembly criteria			
Number and name		**Rating**	
C_1	Number of materials in the assembly	One	1
		Two	0,6
		More than two	0
C_2	Assembly impact on component design	Low	1
		Medium	0,6
		High	0,2
C_3	Assembly tools	Hand tools	1
		Special machinery	0,6
		Heavy equipment	0

Disassembly criteria			
Number and name		**Rating**	
C_4	Component accessibility	Direct	1
		Indirect, but easy	0,5
		Indirect and difficult	0,2
C_5	Assembly reversibility	Reversible at EoL	1
		Assembly destruction	0,6
		Component destruction	0,2
C_6	Disassembly tools	No tools	1
		Standard tools	0,8
		Specific tools	0,2

$$L = \frac{\sum_{i=1}^{N} C_i}{N} \quad (1)$$

Where:

L is the liaison index [adimensional];

C_i is the value of each criteria i [adimensional];

N is the number of criteria [adimensional].

Step 5: Obtaining recovery rates

In this stage three different recovery rates are established for every product component:

- Theoretical rate (T_R): This is the theoretical recovery percentage of the component. That is to say, if a material is technically recyclable it is expected that 100% of its mass will be recovered.
- Practical rate (P_R): This rate takes into account the existence of recycling facilities as well as their performance. Target components, since they are dismantled, have P_R greater than or equal to components that have not been dismantled, but which are shredded [21].
- Disassembly affected rate (D_R): This indicator assesses the joint's significance and quality from a disassembly point of view. This rate is computed by multiplying the liaison index (L) with the practical rate (P_R). As L takes values to a range from 0 to 1, D_R is lower than or equal to P_R.

Each of these rates is in turn decomposed into three indices:

- % material recovered mass (%m): percentage of the mass that is recovered by reusing, remanufacturing or material recycling.
- % energy recovered mass (%e): percentage of the mass that is recovered in the form of energy (incineration with energy recovery).
- % waste disposed mass (%w): percentage of the mass that is landfilled. This is the difference, in percentages, between the total component mass and the sum of its material and energy recovered mass.

The overall recovery rate of the product can be obtained by adding the rates of all components in proportion to their individual mass compared to the mass of the product.

Step 6: Redesign

The sixth phase of the methodology enables designers to propose alternative designs by modifying assembly technologies. Product disassembly improvement is signalled by obtaining greater liaison indices and recovery rates. The proposed methodology facilitates comparison among designs with different assembly relationships in order to more easily identify the one that offer the best disassemblability.

3.3 Implementation

At this moment the proposed methodology is not available as software. However, spreadsheets were set up in the electronic spreadsheet program Excel. This model allows users to carry out the steps of this methodology. The results are given in several tables and bar charts.

4 CASE STUDY

4.1 Initial study of the product

The approach is applied on an air-cooled liquid chiller in order to show the different stages of the method.

Table 2 shows the list of product components along with their description, assembly technologies and the identification of target components and their EoL scenarios.

The following step consists of setting up physical precedencies between components, which is shown through product's disassembly tree in figure 4.

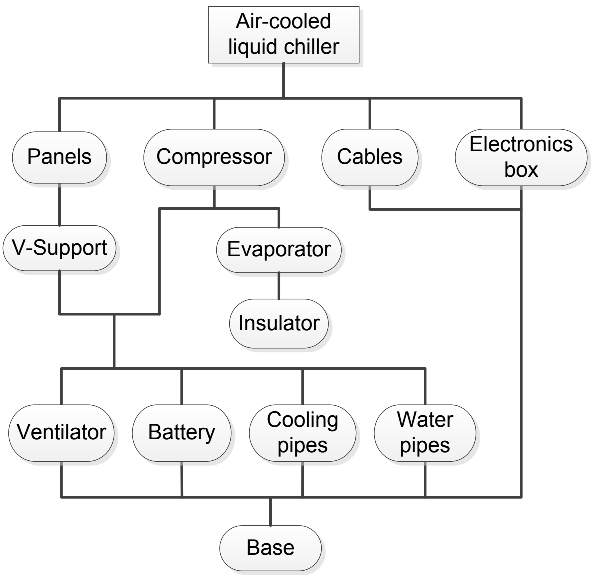


Figure 4: Air-cooled liquid chiller's disassembly tree.

Having identified the target components and having composed the disassembly tree, an evaluation of target components' assemblies and disassemblies is made in order to obtain their liaison indexes (L). Once these indexes are obtained, the three recovery rates are computed for all components. This information is reported in table 3.

The database used to establish the recovery dates is the one developed by Vital [21] with some extrapolations.

4.2 Remarks about the design and product redesign

Target components with lower liaison indexes are the base, the cooling pipe, the battery and the ventilator. This is due mainly to the fact that these items are not directly accessible (criterion 4). To remove them, other elements must be extracted before, which implies in some cases assembly or component destruction (criterion 5). Another fact is that because of the characteristics of the product (heavy and hardy components) the tools used to assemble those components are not standard (criterion 3).

Product redesign involves a change in the assembly method of the cooling pipe to make it reversible at EoL, using standard tools. An improvement of the location of the battery and the ventilator to make them more accessible is also made. No changes are applied on the base since it is a component that is only recoverable when all the other components have been removed. Indeed, its accessibility is indirect and difficult (criteria 4) in any case.

Table 2: Components with their assembly methods and target components' EoL scenarios.

No.	Component	Mass (kg)	Material	Assembly method	Target component	End-of-life scenario		
						Reuse/ Rem.	Recycling	Depollution
1	Base	161	Steel	Screw	Yes	-	X	-
2	Compressor	622	Multi-material	Screw	Yes	X	-	-
3	Evaporator	92	Steel	Screw	No	-	-	-
4	Insulator	1	Foam	Glue	No	-	-	-
5	Water pipe	20	Steel	Screw	No	-	-	-
6	Cooling pipe	11	Copper	Soldering	Yes	-	X	-
7	Battery	138	Multi-material	Screw	Yes	-	-	X
8	V-support	93	Steel	Screw	No	-	-	-
9	Ventilator	65	Metal alloys	Screw	Yes	-	-	X
10	Electronics box	12	Multi-material	Screw	Yes	-	-	X
11	Cables	3	Multi-material	Snap fit	Yes	-	-	X
12	Panel	75	Steel	Screw	No	-	-	-

Table 3: Components' liaison indexes and recovery rates.

No.	Description	Target component	L	T_R			P_R			D_R		
				%m	%e	%w	%m	%e	%w	%m	%e	%w
1	Base	Yes	0,63	100	0	0	95	0	5	60	0	40
2	Compressor	Yes	0,90	75	25	0	68	1	31	61	1	38
3	Evaporator	No	-	100	0	0	95	0	5	95	0	5
4	Insulator	No	-	0	100	0	0	5	95	0	5	95
5	Water pipe	No	-	100	0	0	95	0	5	95	0	5
6	Cooling pipe	Yes	0,60	100	0	0	85	0	15	51	0	49
7	Battery	Yes	0,63	100	0	0	45	0	55	28	0	72
8	V-support	No	-	100	0	0	95	0	5	95	0	5
9	Ventilator	Yes	0,70	100	0	0	70	0	30	49	0	51
10	Fuse box	Yes	0,97	100	0	0	18	43	40	17	42	42
11	Cables	Yes	0,93	100	0	0	24	0	76	22	0	78
12	Panel	No	-	100	0	0	95	0	5	95	0	5

Product overall rates of the old and the new design are shown in figure 5. Theoretical and practical rate (T_R and P_R) are the same for both designs, contrary to the disassembly affected rate (D_R).

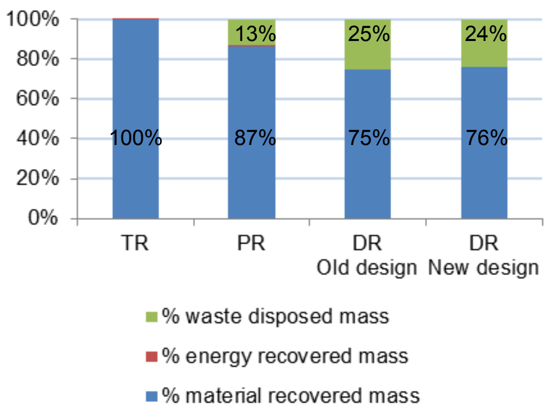


Figure 5: Old design and new design's recovery rates.

With the new design, there is an increase of the material recovered mass and a decrease of the waste disposed mass.

Since the product is mainly composed of ferrous and nonferrous metals, which are materials that cannot be incinerated [21], the energy recovered mass is 0%. Waste disposed mass for the new design is improved by just 1% because target components with low liaison indexes are not the ones with the greatest mass.

5 CONCLUSION AND FUTURE WORK

Designing products under DfD specifications allows them to be better suited for recovery when they reach their end of life. As a result, the resources and the energy required to produce new products are reduced, thus achieving a more sustainable production.

The DfD approach presented in this paper allows taking into account real EoL scenarios so that the effort made on improving disassemblability can be done in a practical way. The assessment of target components' assembly and disassembly leads to establish the liaison indexes, which together with the recovery rates support designers to make choices in order to improve EoL product's treatment.

The methodology presented here is an easy tool to use and does not require extensive knowledge on ecodesign. Besides, the results are easy to interpret and to communicate. On the other hand, this is not a multi-stage ecodesign tool and it is not possible to notice the transfer of impacts. That is to say, by improving product's disassemblability and recoverability it is possible to create new environmental impacts on other life cycle phases of the product, and not being aware of them.

The case study shows that using this approach designers are more conscious of the EoL of the product with regard to improve its recoverability.

Future work has the aim of carrying out some other case studies to test the robustness of the criteria used on the assembly and disassembly assessment. It is also desirable to integrate this tool with other software for modelling and comparing different assembly and disassembly processes in a technological and economical way.

6 ACKNOWLEDGMENTS

The authors would like to thank the organisations that participate in this research, with special thanks to the CETIM technical centre for its financial support.

7 REFERENCES

[1] European Parliament and Council, 2003, Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE), Official Journal of the European Union, 24-38.

[2] European Parliament and Council, 2012, Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), Official Journal of the European Union, 38-71.

[3] Gupta, S. M., Taleb, K. N., 1994, Scheduling disassembly, International Journal of Production Research, 32/8:1857-1866.

[4] González, B., Adenso-Díaz, B., 2006, A scatter search approach to the optimum disassembly sequence problem, Computers & Operations Research, 33/6:1776-1793.

[5] Seo, K.-K., Parl, J.-H., Jang, D.-S., Wallace, D., 2002, Approximate Estimation of the Product Life Cycle Cost Using Artificial Neural Networks in Conceptual Design, The International Journal of Advanced Manufacturing Technology, 19/6:461-471.

[6] Duflou, J.R., Seliger, G., Kara, S., Umeda, Y., Ometto, A., Willems, B., 2008, Efficiency and feasibility of product disassembly: A case-based study, CIRP Annals - Manufacturing Technology, 57/2:583-600.

[7] Östlin, J., Sundin, E., Björkman, M., 2009, Product life-cycle implications for remanufacturing strategies, Journal of Cleaner Production, 17/11:999-1009.

[8] European Commission, 2001, Environment 2010: Our future, Our choice, Communication on the sixth environment action programme of the European Community.

[9] Favi, C., Germani, M., Mandolini, M., Marconi, M., 2012, LeanDfd: A Design for Disassembly Approach to Evaluate the Feasibility of Different End-of-Life Scenarios for Industrial Products, Leveraging Technology for a Sustainable World, 215-220.

[10] Huang, C.-C., Liang, W.-Y., Chuang, H.-F., Chang, Z.-Y., 2012, A novel approach to product modularity and product disassembly with the consideration of 3R-abilities, Computers & Industrial Engineering, 62/1:96-107.

[11] Gerrard, J., Kandlikar, M., 2007, Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery, Journal of Cleaner Production, 15/1:17-27.

[12] Tchertchian, N., Millet, D., Pialot, O., 2013, Modifying module boundaries to design remanufacturable products: the modular grouping explorer tool, Journal of Engineering Design, 0/0:1-29.

[13] Kroll, E., Hanft, T. A., 1998, Quantitative evaluation of product disassembly for recycling, Research in Engineering Design, 10/1:1-14.

[14] Das, S. K., Yedlarajiah, P., Narendra, R., 2000, An approach for estimating the end-of-life product disassembly effort and cost, International Journal of Production Research, 38/3:657-673.

[15] Kuo, T. C., 2012, Waste electronics and electrical equipment disassembly and recycling using Petri net analysis: Considering the economic value and environmental impacts, Computers & Industrial Engineering, 65/1:54-64..

[16] Yi, H.-C., Park, Y.-C. Lee, K.-S., 2003, A study on the method of disassembly time evaluation of a product using work factor method, IEEE International Conference on Systems, Man and Cybernetics, 2:1753-1759.

[17] Aşkıner, G., 2006, Evaluation of connection types in design for disassembly (DFD) using analytic network process, Computers & Industrial Engineering, 50/1-2:35-54.

[18] Sonnenberg, M., 2001, Force and effort analysis of unfastening actions in disassembly processes, New Jersey Institute of Technology.

[19] Ishii, K., Eubanks, F., 1993, Life Cycle Evaluation of Mechanical Systems, Proceedings of the 1993 NSF design and manufacturing systems conference/SME, 1:575-579.

[20] Kuo, T. C., 2006, Enhancing disassembly and recycling planning using life-cycle analysis, Robotics and Computer-Integrated Manufacturing, 22/5:420-428.

[21] Vital, X., 2006, Eco'DEEE, Eco-conception des produits électrique et électroniques en vue du recyclage, CODDE.

10.4 Sustainable water reuse resulting from oily wastewater of the manufacturing industry

J. F. Souza [1,2], J.O. Gomes [2], E. Y. Kawachi [2]

[1] Department Mechanics Engineering, Universidade Tecnológica Federal do Paraná, Paraná, Brasil

[2] Department Mechanics Engineering, Instituto Tecnológico de Aeronáutica, São Paulo, Brasil

Abstract

A key element of sustainability is the prudent use of natural resources. This means using non-renewable resources efficiently and developing alternatives to replace them in the future, while using renewable resources in ways that do not endanger the resource or cause pollution. It is known that oil-based cooling is one of the most unsustainable elements of machining processes. The effect of cutting fluids on the environment is widely recognized by users of machine tools, particularly with regard to their degradation and ultimate disposal as a major problem. Faced with this problem this article seeks to define the requirements and restrictions of water resulting from the effluent treatment of cutting fluids, so that this can be reused in the machine tools.

Keywords:

Cutting fluids, Microbiological Monitoring, Treatment of oily industrial effluents, Water reuse.

1 INTRODUCTION

The conciliation of the constant quest for competitiveness with the growing necessity of preserving natural resources, especially water. This is the present great challenge of companies worldwide, especially in industries, increasingly pressured by performance indicators as well as social and environmental responsibilities.

This article seeks to define the requirements and restrictions of water resulting from the effluent treatment of cutting fluids at the end of its useful life in transformation industries, with the aim of reusing the water from these effluents again in machine-tools. The reasons for closing this cycle of the reuse of water is due to some factors such as: present cost of water, compliance with the requirements of environmental control entities and preservation of the environment.

There are various forms of reusing water, but in most cases the treated water is not reused for the same purpose, due to the fact that there are no efficient means of treatment with low energy cost. In general, this type of industrial water retains in its composition some elements which are harmful to the environment and of difficult degradation. Another issue to be considered is the high cost of this type of process, causing the industrial practice to be unfeasible.

Three effluent treatment technologies were analyzed, (chemical, thermal and photochemical by UV/H_2O_2) and tests were performed to verify the efficiency of emulsions prepared with different types of water, in order to evaluate the feasibility of reusing water from emulsions discarded in the machining process. Preliminary information demonstrated that the methods are efficient for treating water from emulsions; nevertheless, the remaining organic and metallic volumes are elevated and make the reuse of this water impracticable for the preparation of emulsions. Furthermore, the costs incurred for reusing the water are lower when compared to the use of water from water supplies, which justifies the search for adequate treatment methodologies for this type of effluent.

The results of the proposed tests may offer a perspective for a closed cycle, where the water used in the preparation of the cutting fluids may be recycled locally and reused for the preparation of new fluids. In this manner the loss of water will only occur during the transformation processes, for example, with chip dragging or through evaporation and no longer in post-treatments, where, at present, industries do not reuse the water in new emulsions.

.

2 PROCESSES USED IN THE TREATMENT OF OILY INDUSTRIAL EFFLUENTS

In this study, three of the various types of effluent treatments used by the industries were analyzed.

2.1 Thermal Process

The thermal breakdown is a physical process that dispenses the use of chemical products. The emulsion is removed by means of evaporation, the aqueous phase, and the oil remains due to its higher boiling point. The evaporated water is condensed and by means of an additional stage, the oily residues dragged by the vapor are removed. The advantage of this process is that it does not produce sludge and the purity of the separated water is free of salts, but the high cost of the operations arises as the disadvantage [1] [2][3][4].

2.2 Chemical Process

In the chemical processes, acids are added in order to breakdown the emulsions by degradation of the emulsifiers. The chemical reaction may be reinforced by the addition of metallic salts. These salts react to the emulsion separating it into phases, permitting the removal of the oil from the surface of the fluid in the emulsion treatment tank [1][2][5].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

2.3 Photochemical Process - UV/H_2O_2

Also known as degradation process by chemical oxidation, more commonly called advanced oxidation process. These are promising industrial effluent treatment systems, because they permit the degradation of organic compounds which cause the contamination to the water, mainly the recalcitrants, transforming it into CO_2 and H_2O in relatively short reaction periods.

These are based on the generation of the hydroxyl radical (OH), of a strongly oxidant characteristic (E° = 2.8V), and which can foster the degradation of various organic contaminants, incorporating hydrogen and generating organic radicals (equation 1). The addition of molecular oxygen causes the production of peroxide (equation 2), which is not stable and tends to react with other materials forming more simple compounds [6].

$$HO^{\bullet} + RH \rightarrow R^{\bullet} + H_2O \tag{1}$$

$$R^{\bullet} + O_2 \rightarrow RO^{\bullet}{}_2 \tag{2}$$

Processes based on the UV/H_2O_2 systems emerged as alternatives for the degradation of industrial residues. The benefic effects observed with the use of ultraviolet radiation combined with the hydrogen peroxide, when compared to the isolated application, are in the fact that the rate of generation of free radicals is significantly increased in the case of the combined technique. In the UV/H_2O_2 process the effluent to be treated is first mixed with H_2O_2 and, next, submitted to ultraviolet radiation [6].

3 OBJECTIVE

The main objective of this study was with reference to the treatment of the aqueous phases of an oily effluent from metal-mechanic industries, using three effluent treatment methods:

a) Advanced oxidation process – AOP using UV/H_2O_2;
b) Chemical treatment – acid breakdown;
c) Thermal treatment – evaporation.

As well as evaluating the possibility of reusing the treated effluent in a pilot scale by means of the High Speed Machining (HSM) process. To attain the objectives, the following work phases where proposed:

a) Analysis of the water treated in each of the treatments for the COD and BOD solid concentration parameters;
b) Evaluation of the performance of the cutting fluid emulsioned with the treated water, with reference to the following parameters: stability of the emulsion and damages to the machine structures.

Four separate emulsions were prepared:

1) the first with water supplied by the water supply network;
2) the second prepared with reused water from the thermal treatment,
3) the third from effluents resulting from the photochemical treatment,
4) and the fourth with water resulting from the chemical treatment, which was not successful because no emulsion was formed (this method was rejected for the machine tests).

In all the cases, with the exception of the 4th, machining tests were performed in order to verify the performance and behavior of the emulsions prepared with the different types of water.

4 MATERIALS AND METHODS

Cutting fluids were collected from discharges of machine-tools of the CCM/ITA Laboratory (ITA's Manufacturing Competence Center). Three types of treatments were performed with these oily effluents: thermal, chemical and photochemical.

After each treatment the resulting water was submitted to chemical and microbiological analysis in order to verify the quality and efficiency of each method.

In sequence the possibility of reusing the water resulting from each treatment method in the reformulation of new emulsions was verified.

The treated water from thermal and photochemical treatments was used to prepare emulsions for the cooling system of the HSM machining center. During the useful life of these fluids their stability and maintenance were accompanied and managed daily.

Before executing any of the treatments (chemical, thermal or photochemical) a pre-treatment was performed, in other words, a rough separation of the effluent's water/oil, with the main function of separating the emulsion phases: oily and aqueous.

After receiving this pre-treatment the oily phase was conducted for re-refining (added value) and the aqueous phase (without any value) directed to one of the treatments to be analyzed.

In the case of the photochemical treatment, a glass reactor with a capacity of 0.500 l, coated with a jacket cooled with the passage of water at room temperature. Before beginning the irradiation, 1.2 ml of hydrogen peroxide was added at 1000 ppm concentration, in 0.450 l of effluent. The effluent was irradiated using a mercury vapor lamp of 125 W (without the protector bulb), inserted in the solution by means of a quartz bulb and the irradiation period fixed at 135 minutes. The distance between the lamp and the surface of the effluent was of 12 cm. The solution was magnetically agitated with constant bubbling of oxygen at a flow of 80 ml/min.

4.1 Physical and chemical characterization of the effluent

The pH of the effluents was determined by MICRONAL pH Meter, model B-374, according to the ASTMD 1293-84 standard [7][8][9]. The total solid content in the effluent was determined by the APHA (1992) standard method. A 100 ml sample of the effluent was placed in a rounded glass beaker, concentrated by vacuum and dried in an oven at 105 ± 3ºC to constant mass [7][8][9]. Chemical and microbiological analyses were performed in the CTMSP laboratories in order to obtain quantitative information of the degree of saturation of the emulsions and of the treated waters. Among the chemical analysis performed, the following were included: pH, conductivity, turbidity, alkalinity, chlorites, ammonia, total hardness, calcium hardness, nitrates, phosphate content, phosphorus, content of iron and total solids.

4.2 Determination of the Chemical Oxygen Demand (COD)

The COD is based on the chemical oxidation of the organic matter by means of potassium dichromate at high temperatures and in acid containing a catalyzer. The determinations were performed in accordance with the procedure described in the APHA (1992) standard [6] [7].

4.3 Determination of the Biochemical Oxygen Demand (BOD)

The BOD5 corresponds to the quantity of oxygen necessary for aerobic microorganisms to mineralize the carbonate organic matter of a sample, under the conditions of the analysis [7][8][9]. The quantity of biodegradable organic matter in the sample was determined by the difference of concentration of the oxygen dissolved before and after incubation for 5 days of the samples at 20 ± 1ºC, away from light. Determinations were made in accordance with the procedures described in standard NBR 12614/1992 [9][10].

4.4 Microbiological Monitoring

For the evaluation of the presence of fungus and bacteria in the water the Gram coloration method was used, which classifies the bacteria into two groups, Gram positive (low concentration of lipids in its membranes) and Gram negative. The denomination gram positive or gram negative is due to the difference between the membranes of the bacteria [8][10].

4.5 Tests on Machining Equipment Using Treated Water

After the performance of the above analysis the possibilities of preparing new emulsions with the water resulting from each of the treatment methods for use in the machine tests was verified.

Machining tests were performed in order to verify the efficiency of the emulsion with reused water. Machining was evaluated by means of the following tests:

- Signs of oxidation of machine-tools;
- Analysis of the cutting fluids in the storage mechanisms of the machine-tools;
- Microbiological analysis;
- Analysis of the useful life of the fluid;
- Signs of oxidation of the machined parts.

During this phase the HSM Hermler machining center of the CCM-ITA was used.

Since no specific papers were located in the literature consulted for the reuse of water from machining processes, for this work comparative parameters were adopted using the water supplied by SABESP and the reused water.

5 RESULTS

When an oily emulsion used in machining metals loses its specific functions, this oil is no longer a consumption material for the operation, but a residue, therefore must be directed to the effluent treatment station. In this item the results of the analysis with the waters resulting from the three treatment methods of the aqueous phase of soluble cutting fluids.

Table 1 presents the results relating to the determination of pH, concentration of solids, COD and the characterization of the aqueous phase of oily effluents without passing through any type of treatment and the water resulting from the treatments analyzed compared to the results of the water from the water supply network (SABESP).

Despite the breakdown of the emulsion of the oily effluent, the aqueous effluent presented a high COD which could be attributed to the presence of dissolved organic matter.

The BOD, which represents the biodegradable organic matter, cannot be determined even when diluting the effluent up to 20 times, with the exception of the effluent with thermal treatment. These results confirm the observations of Cheng et al. [1][2][3][10], with reference to the low biodegradability of this type of effluent.

Table 1. Characterization of the aqueous phase of the effluent without treatment on a bench scale (Caption – ND: Non determined; T1: Aqueous phase without treatment; T2: Aqueous phase thermal treatment; T3: Aqueous phase chemical treatment; T4: Aqueous phase photochemical treatment; T5: Water from the water treatment network (SABESP)).

Parameters	T1	T2	T3	T4	T5
pH	7.93	7.0	6.7	11	6.7
Concentration of total solids (g/L)	16	0.062	8.0	16.5	0.06
COD (mgO_2./L)	3650	1500	75	1015	0
BOD (mgO_2./L)	ND	850	ND	ND	0

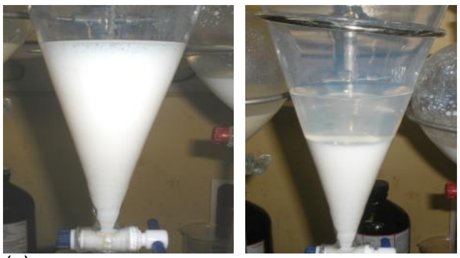
After the photochemical treatment the COD value reached 1015 $mgO^2.L^{-1}$ and, this represented a 72% reduction in relation to the result of the effluent without treatment (Table 1).

The photochemical treatment was effective only for the reduction of COD. Therefore, it can be concluded that the effluent should not be discharged to the receptive body, because the remaining parameters characterizing the aqueous phase in Table 1 were not adequate. With reference to the stability of the emulsion prepared with the treated effluent, in the case of the photochemical treatment, it was verified that the still fluid in the storage tank, without constant circulation became destabilized, and this could be attributed to the concentration of inorganic substances present in the effluent. Pusavec [3][5][6][7][8][9] described that mainly calcium, magnesium, iron and occasionally aluminum, can react with the emulsifying agents in the soluble oil and destabilize the emulsion.

Figure 1(a) presents a sample of the stabilized emulsion, prepared with water from the water supply network and/or from thermal treatment, and figure 1 (b) a sample of emulsion prepared with water from the photochemical treatment, after resting it presented a separation of phases (break of emulsion). This same situation occurred when the preparation of emulsion with water from chemical treatment was attempted, which proved to be unfeasible.

On the other hand, the stability of the emulsion prepared with the effluent from the thermal treatment presented normal working conditions during the total period of the test, similar to emulsions prepared with water from the water treatment network (SABESP), in other words, potable water.

Another aspect observed in the test with water from the photochemical treatment was the appearance of points of oxidation in the machined parts, after these remained static inside machine-tools. The same oxidation points were observed in the internal structure of the machine. Due to these problems the tests with water from photochemical treatment were interrupted in order to avoid further damages to the machine-tool structure. It is believed that this oxidation and the break of the emulsion could be attributed to the results: of the pH, conductivity, and of the presence of microorganisms.



(a) (b)

Figure 1: (a) Stable emulsion – SABESP and/or thermal treatment water and (b) destabilized emulsion – water from photochemical treatment.

The costs of the evaluated treatments are different. The evaporation method is most efficient but also more expensive, because it is a method which consumes a lot of electric power, which is a negative aspect because it is only feasible for large sized companies. The chemical method is the most economic, because it uses simple reagents, nevertheless the water resulting from this treatment does not present adequate conditions for reuse in the preparation of new emulsions. The photochemical treatment also presents a high operational cost in the system used. With the latter it was possible to emulsify a new emulsion, but the method still needs some technical alterations in order for the system to become more adequate for the machining process.

By means of the tests performed it was observed that the water resulting from evaporation treatment may be used in the preparation of new emulsions, although it presents some disadvantages, such as:

a) The high cost of the treatment;
b) The resulting water does not have a composition similar to the water supplied by the water supply network;
c) The contamination by microorganisms in this type of water is easier and quicker.

The chemical treatment, despite being economically feasible, for this type of effluent treatment, it is not adequate for the reuse of the water because for this to be possible it would be necessary to add to the process other phases, which would eliminate the contamination by microorganisms, removing all the unnecessary compounds introduced during water/oil separation, and remove all the surfactants/emulsifier still present in the composition of this treated water.

Table 2 presents the results of the chemical analysis performed on the samples of water resulting from the thermal and chemical treatments compared to the results obtained for the water from the water treatment network (SABESP).

The elevated values of nitrites and phosphates could be related to the anti-corrosive additives included in the cutting fluid and not efficiently removed during the treatment of the water. Further, high contents of N and P could favor the development of cyanobacteria and other microorganisms that use nitrogen and phosphorous as nutrients. In this manner, both these waters presented elevated values of nutrients, and the decrease of these values would be recommended for the reuse of the water.

This tendency is also confirmed by the elevated BOD values (Table 1), which indicate the quantity of oxygen necessary to oxidize organic matter by aerobic microbial decomposition. In the case of the chemically treated water, the cellular growth could occur without nutritional limitations, since sources of C (BOD), N (ammonia and nitrites) and P (phosphates) are high.

The quantity of oxygen necessary to oxidize organic matter by chemical agents (COD) of the treated waters indicate the high organic load of these waters, especially for the chemically treated water, which presented values 20 times greater than for the thermally treated waters. This could justify the break in the emulsion visualized in Figure 1(b), indicating the saturation of the chemically treated water. Also, the presence of iron in the water during the chemical treatments causes the formation of small flakes, that slowly sediment, which could have caused the high quantity of total solids.

In the case of the thermally treated water, the organic load, although high, is less than that of the chemically treated water, due to a greater efficiency in the separation of the oil by membrane, prior to the heating phase.

However, this method is propense to carrying volatile substance (such as ammonia, chlorides and bicarbonates), in a manner that the alkalinity defined by the presence of calcium and magnesium bicarbonates also contributes towards the increase of the hardness of the water.

Table 2: Results of the chemical analysis of the chemical and thermal treatments compared to the results of the water from the water supply network.

Analysis of the water	Water from evaporation	Water from chemical breakdown	SABESP water
pH	70	6.7	6.7
Conductivity (µs/cm)	97.7	81	81
Turbidity [NTU]	5.6	1.5	1.5
Alkalinity (ppm)	58.28	20.17	17.94
Chloride (ppm)	0	18.85	17.95
Ammonia (ppm)	97.11	0.22	0.22
Total hardness (ppm)	44.69	16.53	15.92
Calcium hardness (ppm)	0	16.53	15.92
Nitrites (ppm)	7.87	9.53	0.2
Phosphate content (ppm)	0.805	1.086	0.44
Phosphorus (ppm)	0.14	0.354	0.32
Iron content (ppm)	0.35	2.73	0.31

In the case of table 3 it is possible to visualize the presence of some inorganic substances in the water resulting from the photochemical treatment compared to the values foreseen under CONAMA 357 Resolution [1] [2] [3] [4].

In accordance with the CONAMA 357 Resolution, Art. 34, only the sulphur compound (260 mg. l^{-1}) is outside the acceptable limits (1 mg.l^{-1}).

Restricted ions, such as iron, barium, manganese and zinc were detected below the limit foreseen by the previously mentioned resolution and the ions determined in greater concentrations, such as calcium, potassium, magnesium and aluminum are not restrictive.

The total concentration of ions determined for water resulting from the photochemical treatment was of 1.3 g.l^{-1}, which corresponds to 8% of the total solids reported in table 3, indicating that organic compounds predominate in this water.

Table 3: Concentration of inorganic compounds present in water from the photochemical treatment Caption: NF – not foreseen

Parameter	Values found (mg.l^{-1})	Effluent discharge standards (mg.l^{-1}) CONAMA – 357/2005
Calcium	106	NF
Sodium	1160	NF
Potassium	42.8	NF
Magnesium	7.6	NF
Aluminum	4.1	NF
Iron	0.9	15.0
Barium	0.05	5.0
Strontium	0.8	NF
Manganese	0.02	1.0
Zinc	0.3	5.0
Sulphur	260	-
Total	1323	-

5.1 Microbiological Analysis

In the microbiological analysis of the water resulting from the thermal treatment (evaporation) no bacteria or fungus were found. But in the water resulting from the photochemical treatment, bacteria colonies of the type E. coli (Gram negative) were found. In the case of the water resulting from the chemical treatment, various colonies of bacteria of the Gram negative type were found (*klebssiella pneumonae* and *Enterobacter sakazakii*) as well as fungus (*Fusarium sp* known as yeast and *Cephlosporium sp* the popular mould on food).

By means of these results it is verified that the thermal process is more efficient in relation to the elimination of microorganisms from the treated water, because during the process the effluent is headed to high temperatures. The chemical and photochemical treatments are not efficient in the issue of decontamination of oily effluents.

5.2 Analysis of the Machine

During the test period it was observed that the emulsion made with water from the water supply system maintained the pH without alteration for five months. When using the emulsion prepared with water from the thermal treatment, the pH altered in the second month of the tests. This result could be justified by the statement of the prior paragraph, which mentions the facility of contamination to the water resulting from the evaporation treatment. In the case of the emulsion prepared with water from the photochemical treatment, the pH also altered during the first days of the tests.

Another disadvantage observed during the tests on the machines was the strong smell of the emulsion prepared with water from the thermal treatment.

6 CONCLUSIONS

It was verified that the three cutting fluid treatment processes (chemical breakdown, photochemical and thermal) comply with the standards established by the regulatory agencies, but according to these results there is a necessity to discover more efficient and economic means of treating soluble cutting fluid effluents, because the water resulting from these processes, though acceptable according to the standards, cannot be reused in machine-tools, closing the rational use cycle, permitting that a greater volume of water remains available for noble uses, avoiding losses and unnecessary disposal. Further, if it were possible, there would e economic benefits, because of cost reductions with the water consumption tariffs and of industrial wastewater.

The photochemical treatment was efficient in the COD reduction, reaching values of up to 72%, but it was not capable of reducing the proliferation of microorganisms.

In relation to the stabilization of the emulsion, it is observed that, if there were a constant recirculation of the emulsion inside the cooling circuit, the cutting fluid could be stable, mischaracterizing the separation of the phases, even with the presence of inorganic substances in the effluent.

With regards to the machine and the machined parts, it can be concluded that the oxidation points which appeared in some parts of the machine and of the machined parts could have occurred due to the presence of inorganic compounds in the effluent, which could be removed by means of the submission of the effluent to a demineralization process by ionic exchange.

Based on the results obtained, the necessity of performing specific machining tests was verified (drilling, milling, threading), which could better evaluate the performance of the cutting fluids in relation to lubrication and cooling. Also, the addition of biological treatments to future researches in order for the treatment systems to become less aggressive.

7 ACKNOWLEDGMENTS

The authors express their gratitude to the Fundação Araucária and CNPq (Brazilian Council for Scientific and Technological Development), for the financial support for the study.

8 REFERENCES

[1] Tomala, A., Karpinska, A., Werner, W.S.M., Olver, A., Störi, H., 2010. Tribological properties of additives for water based lubricants. Wear 269, 804-810.

[2] Cheng, C., Phipps, D. Alkhaddar, R.M., 2006. Thermophilic aerobic wastewater treatment of waste metalworking fluids. Water and Environment 20, 227-232.

[3] Schoeman, J.J., Novhe, O., 2007. Evaluation of microfiltration for the treatment of spent cutting-oil, Water SA 33, 245-248.

[4] Kobya, M., Ciftci, C., Bayramoglu, M., Sensoy, M. T., 2008. Study on the treatment of waste metal cutting fluids using electrocoagulation. Separation Purification technology 60, 285 – 291.

[5] Pusavec, F., Kramar, D., Krajnik, P., Kopac, J., 2010. Transitioning to sustainable production – part II: evaluation of sustainable machining technologies. Cleaner Production 18, 1211-1221.

[6] Monteiro, M.I., 2006. Tratamento de efluentes oleosos provenientes da indústria metal mecânica e seu reuso. Tese (doutorado) – Universidade de São Paulo, Escola de Engenharia de Lorena, p. 148.

[7] ASTM D1293 – 12: Standard test methods for pH water. Rev. November, 2012.

[8] APHA: Standard Methods for examination of water and wastewater. Washington DC: American Public Health Association, 1998. 20 ed.

[9] NBR 12614 –. Águas – Determinação da demanda bioquímica de oxigênio (DBO) – método de incubação, 2012.

[10] Gonçalves, J.F.S. Proposição de método de desenvolvimento de fluido de corte de base vegetal. Tese (doutorado) – Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, p. 223.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

10.5 Market driven emissions associated with supplying recovered carbon dioxide to sustainable manufacturing applications

Sarang D. Supekar, Steven J. Skerlos*
Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109-2125, USA

Abstract

This paper presents a life cycle assessment (LCA) framework for quantifying marginal emissions associated with the use of recovered carbon dioxide (CO_2) in sustainable manufacturing applications. A consequential LCA approach is applied to estimate marginal emissions from various steps in the recovered CO_2 supply chain such as capture, separation, and transport. These emissions are allocated to the CO_2 producer or the end user considering market forces, technology application, and product substitution. Additionally, a GHG accounting method is proposed that distinguishes between CO_2 generation and CO_2 emission to account for direct emissions from the recovered CO_2 supply chain. The approach is demonstrated in the context of a case study that considers using recovered CO_2 from an ammonia plant as an input to a machining process using supercritical CO_2-based metalworking fluid.

Keywords

Carbon Dioxide Reuse, Consequential Life Cycle Assessment, Green House Gas Accounting, Pollution Prevention, Technology Diffusion

1. INTRODUCTION

Carbon Dioxide (CO_2) is being widely considered as an environmentally benign substitute material in applications such as pharmaceutical production [1], polymerization [2], semiconductor manufacturing [3], metal component cleaning [4], and metals forming and machining [5]. The benefits of substituting existing process fluids with CO_2 are well known and include the elimination of numerous environmental concerns ranging from toxicity, to energy consumption, to water consumption. However, allocation methods used in traditional (attributional) life cycle assessment (LCA) may lead to gross overestimation of environmental impacts involving the use of recovered CO_2. Additionally, current greenhouse gas (GHG) accounting practices may place the burden of the reused CO_2 emission on these sustainable manufacturing technologies, especially in the event of a carbon tax introduction.

From a technology diffusion standpoint, overestimation of environmental impacts of using recovered CO_2 can act as a deterrent to its adoption, despite providing multiple environmental and health benefits. As a result this paper presents a framework to quantify the marginal emissions associated with the use of recovered carbon dioxide (CO_2) using a consequential life cycle assessment approach and a supporting greenhouse gas accounting methodology, so that the true environmental impacts from the use of CO_2-based process fluids in production systems can be assessed.

2. LCA AND GHG ACCOUNTING FRAMEWORK

2.1. Allocation and System Boundaries

A vast majority of the merchant CO_2 that is used today is recovered as a byproduct during the manufacturing of chemical products such as ammonia, hydrogen, and ethanol (hereafter referred to as primary market products) using chemical solvents, physical adsorption or membranes. Many of the plants that produce these primary market products simply release the CO_2 to the atmosphere without recovering it for sale in the merchant CO_2 market. In fact there are only about 100 plants recovering CO_2 in the United States, which is sourced and distributed in the merchant market by about five major companies. The limited supply of recovered CO_2 is due to relatively low demand for CO_2. As a result, marginal demand for CO_2 is unlikely to influence the production of the primary product such as ammonia or hydrogen.

A mass or volumetric allocation approach typically used in attributional LCA would suggest that recovered CO_2 should be allocated 50-90% of the environmental impacts associated with the production of the primary market product. This approach directly attributes environmental impacts to recovered CO_2 that were not *caused* by the recovery of CO_2. This both defies logic and deters use of recovered CO_2. Some studies have used a market price-based allocation [6] to address these issues, which results in lower impacts attributed to the recovered CO_2 since the price of CO_2 is significantly lower than that of the primary market product. The approach still does not lead to causal emissions being attributed to recovered CO_2, and faces additional problems identified by Overcash et al. [7] who noted that the demand and economic value of the primary market product and recovered CO_2 vary in manners irrelevant to environmental emissions. Thus, given that the demand for recovered CO_2 does not affect the production of the primary market products, a different approach is needed to estimate the real marginal emissions from the recovery of CO_2.

The allocation approach proposed in this framework is "market-based" and follows the approach outlined by Ekvall and Weidema [8]. The approach is rooted in consequential LCA (cLCA) methodology, which emphasizes the need to allocate emissions on a causal basis. In the case of recovered CO_2, a cLCA approach accounts only for the deployment and operation of marginal technologies employed by the producers of the recovered CO_2. The direct emission of the recovered CO_2 in the reuse application (e.g., machining process or soda drinks) is

* Corresponding author. *Tel.*: +1 734 615 5253, *Fax*: +1 734 647 3170
E-mail: skerlos@umich.edu

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

attributed to the primary market product that originally generated the CO_2. The cLCA methodology includes any significant differences in the environmental burdens from the transportation, use and waste management of CO_2, compared to the transportation, use and waste management of products and processes replaced by CO_2. We also expand the system boundary to encompass the production of other products or processes whose use is affected by the use of CO_2. For instance, the application of recovered CO_2 in manufacturing displaces traditional metalworking fluids and maintenance systems, and may extend tool life as well. The credit for the avoided impacts from the technologies displaced by CO_2 is

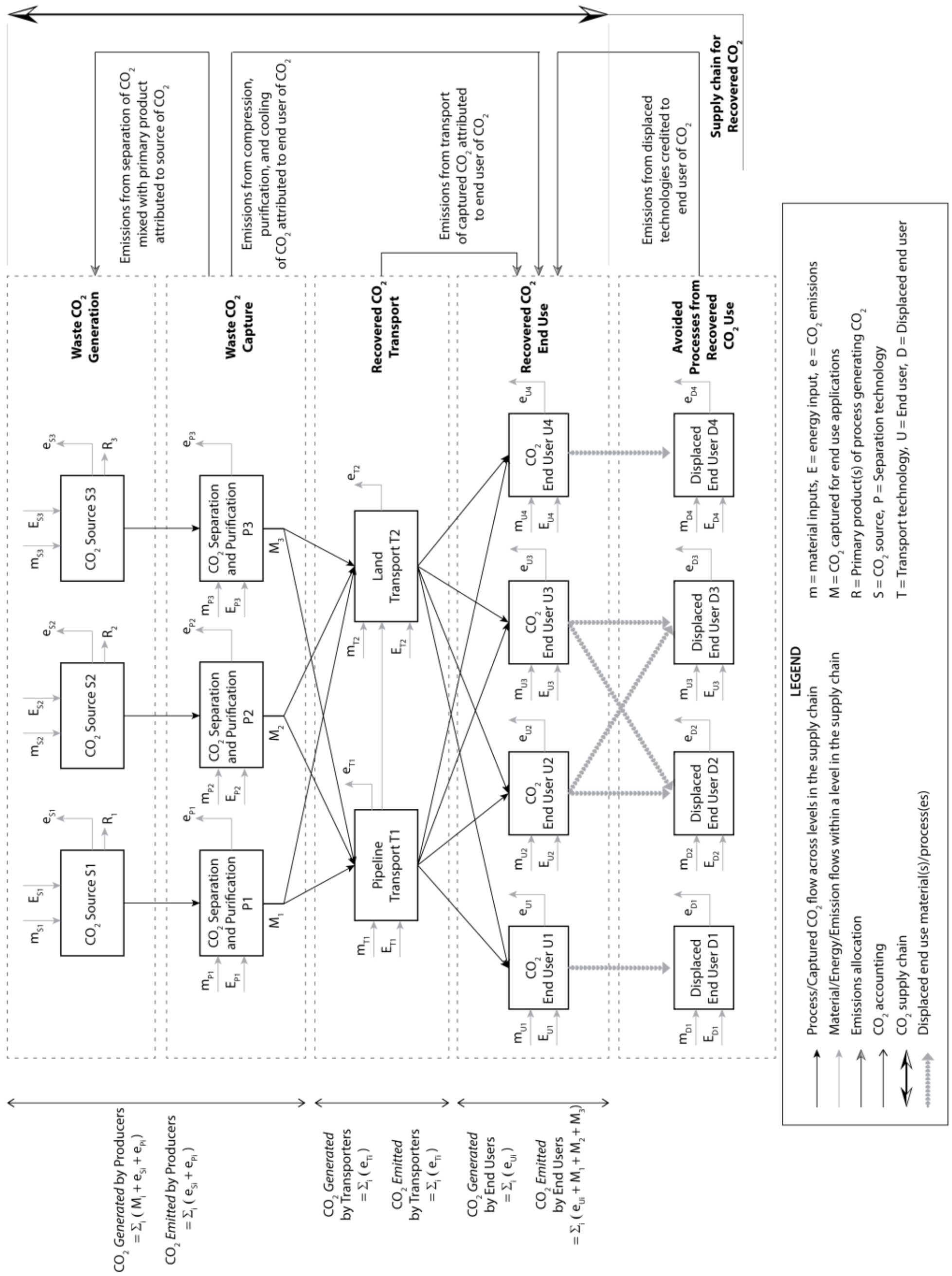


Figure 1: Recovered or waste CO_2 supply chain. Emissions allocations and greenhouse gas accounting methodology used in the framework are indicated.

given to the recovered CO_2 end user.

2.2. GHG Accounting

The World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) provide guidance for GHG accounting for businesses and organizations [9]. Companies first define their organizational boundary by using an 'equity' or 'control' based approach. Then there are operational boundaries within these organizational boundaries, which divide emissions into three 'Scopes'. Scope 1 accounts for direct emissions that occur from operations owned or controlled by the company. Scope 2 accounts for emissions due to generation of electricity that is purchased by the company and its entities. Lastly, Scope 3 is an optional reporting category that encompasses all other indirect emissions (e.g., upstream production processes associated with materials used by a company). While the current WRI guidelines on operational boundaries clearly distinguish between direct (Scope 1) and indirect (Scope 3) GHG emissions from an organization, they do not distinguish between GHG generation and GHG emission. The WRI guidance document only mentions that (regulatory) compliance schemes are more likely to focus on the point-of-release of emissions. On this basis it is claimed that making a distinction between generation and release may not matter.

On the contrary, the cLCA approach inherently necessitates distinguishing between generation and emission of CO_2. Since Scope 1 does not distinguish between *generation* of GHGs and their *emission* into the atmosphere, we propose the definition of what we call here "Scope 0", which accounts purely for generation of GHGs. Then Scope 1 is newly defined as the emission on GHGs. By these definitions, the total Scope 0 generation must equal the combined Scope 1 emissions from all points of CO_2 release if the CO2 is used in multiple applications. For organizations that emit all their generated CO_2, their Scope 0 and Scope 1 emissions are equal and WRI guidelines apply.

Based on the allocation approach outlined in the previous section, the global warming potential from the use of recovered CO_2 in a sustainable manufacturing application is the sum of its own Scope 0, Scope 2 and Scope 3 emissions. This revised approach can now serve as a more accurate accounting tool to separately account for CO_2 generation, emission, and avoided emissions. The proposed allocation and accounting method is explained in Figure 1.

3. LCA CASE STUDY

3.1. Background

Metalworking fluids (MWFs) are essential coolants and lubricants used in metal cutting and deformation operations such as turning, milling, grinding, and forming. In their most ubiquitous form, they are formulated as aqueous emulsions of mineral oils with at least a dozen other additives such as surfactants, biocides, corrosion inhibitors, and defoaming agents. Despite their widespread use today, aqueous MWFs have been known to have deleterious effects on human health such as dermatitis, cancer, respiratory disorders, and bacterial infections [10]. Untreated or improperly treated spent aqueous MWF waste can pollute the environment through release of toxic chemicals, BOD, and heavy metals. Aqueous MWFs along with their delivery, recycling, and waste management systems, are expensive and can constitute over 15% of a product's manufacturing cost [11]. Aqueous MWFs also limit the material removal rate and tool life due to poor cutting zone penetration

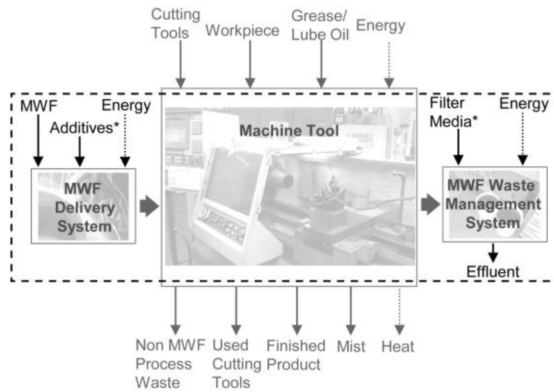


Figure 2: Flows marked in bold typeface fall within the LCA system boundaries indicated by the dotted line. Flows marked * indicate that data for proprietary materials such as extreme pressure additives or resins are not included in the analysis.

[12]. Thus, from a health, environmental, and cost standpoint, there is a need to replace aqueous MWFs with a more sustainable alternative. In this case study, aqueous MWFs thus serve as the displaced end-use technology. The alternate end-use technology is supercritical CO_2 ($scCO_2$) MWF, which is a rapidly expanding solution of lubricant in supercritical CO_2 directed at the tool-workpiece interface through a nozzle. $ScCO_2$ MWF has been shown to significantly increase tool life and material removal rates in numerous machining [13] and grinding applications. Additionally, $scCO_2$ MWF does not pose operator health risks or involve MWF waste management costs. The following sections evaluate the life cycle environmental impacts of applying $scCO_2$ using the cLCA framework discussed earlier. The results are compared with life cycle impacts of two alternatives to conventional MWF that have the potential to improve tool life: high pressure aqueous MWF and Liquid Nitrogen (LN_2).

3.2. Goal and Scope of LCA

The goal of this life cycle assessment is to estimate the marginal environmental impacts from the use of $scCO_2$ in machining and to compare the impacts with those of competing alternative MWF technologies in the market. Aqueous MWFs are assumed to be a 5% aqueous emulsion of semi-synthetic oil containing surfactants and biocides as per the formulation specified in Byers [14]. System boundaries used in the analysis are shown in Figure 2. Emissions from production of the machine tool and auxiliary machines such as MWF handling systems are excluded from the analysis. Emissions from wastewater treatment were found to be negligible and excluded from the analysis. For all MWFs, cradle-to-gate data on emissions, energy use, and water use were used for each component of the MWF considered in the analysis. Inventory data for CO_2 production from ammonia manufacturing was obtained from [7]. Emissions data from natural gas use at the ammonia plant were obtained from the Argonne National Lab GREET database [15]. Inventory data for U.S. average energy mix, vegetable oil in $scCO_2$ MWF, all components of aqueous MWFs, and materials used in aqueous MWF recycling and waste treatment were obtained from the SimaPro 7.3.3 database [16]. Energy emissions were calculated using the U.S. average energy mix. Emissions from transportation of compressed CO_2 and LN_2 were obtained from the NREL US LCI database [17]. Environmental impacts were evaluated for the following mid-point categories: 100 year global warming potential, Ozone depletion potential, photochemical smog formation potential, acidification potential, eutrophication potential, respiratory effects, ecotoxicity, total energy use, and fresh water use.

3.3. Functional Unit and Reference Flow

The functional unit is chosen as the service provided by a MWF system at a machine tool in a medium-size manufacturing facility in Detroit, MI machining Inconel alloy workpieces over a period of one year. Inconel is chosen as the workpiece material because of its recalcitrant machinability, which necessitates the use of MWFs with high heat removal capability (e.g., this rules out traditional minimum quantity lubrication as an option). It is assumed that the machine tool operates for two 8-hour shifts a day for 251 working days in a year with a utilization factor of 60%. The reference flow for the analysis is then the quantity of a MWF used at the facility over a period of one year.

3.4. CO_2 Allocation

In the ammonia manufacturing process, CO_2 is produced during a shift conversion reaction in which CO (produced along with H_2 from the reaction of methane with steam) is oxidized. This CO_2 has to be separated before the N_2 and H_2 present in the stream can react to form ammonia. Thus, the emissions inventory of the steps involved in CO_2 separation are allocated to ammonia. The separated CO_2 can be released into the atmosphere or compressed and refrigerated for being sold in the merchant market. Impacts from the production and maintenance of post-separation CO_2 processing and storage equipment are to be allocated to the end users of the merchant CO_2. In this case the end use is scCO_2 MWF in an Inconel cutting process. Impacts from the operation of post-separation CO_2 processing equipment to produce the reference flow amount of CO_2 used by the scCO_2 MWF are allocated to the cutting process.

3.5. Results and Discussion

Figure 3 illustrates how price-based allocation for CO_2 obtained as a byproduct of ammonia manufacturing can lead to over-estimation of environmental impacts of scCO_2 MWF by a factor of about 10. This overestimation is actually less than a mass-based allocation, which leads to an overestimation by a factor of 40 (this is because a mass based allocation attributes 54% of the impacts from ammonia production to CO_2 since ammonia only constitutes 46% of the process output by mass). Such over-of-magnitude overestimates can be expected to inhibit adoption of CO_2 applications in sustainable manufacturing. More generally, the results support the need for a market-based (cLCA) allocation approach for byproducts or co-products that do not impact the production of the main product(s) and have a significantly lower economic value than the main product(s). The results discussed in the following paragraphs assume a market-based allocation for the CO_2 used in scCO_2 MWF.

Figure 4 shows that a majority of the life cycle environmental impacts of scCO_2 MWF come from energy use for the compression and refrigeration of CO_2 at the ammonia plant. The nominal case in this analysis assumes that the manufacturing facility in Detroit, MI sources its CO_2 from the Lima, OH ammonia plant 250 km away through a local industrial gas supplier. As such, the impacts from transportation of CO_2 to the manufacturing facility contribute only about 25% to the total impacts in most impact categories except smog formation potential where it contributes to 60% of the total impacts. Impacts in the global warming potential, smog formation potential, acidification potential, and respiratory effects mid point metrics are strongly correlated to the distance of the ammonia plant from which the CO_2 is sourced.

CO_2 generated at the ammonia plant in the steam reformer and shift converter counts towards its Scope 0 emissions. The CO_2 in the steam reformer is emitted into the atmosphere at the ammonia plant, and constitutes its Scope 1 emissions. The CO_2 from the shift converter is captured at the ammonia plant, and eventually emitted at the manufacturing facility as spent scCO_2 MWF, thus constituting for the manufacturing facility's Scope 1 emissions.

Based on the allocation as well as GHG accounting method proposed in section 2, the CO_2 emitted from the manufacturing facility in the form of spent scCO_2 MWF is not counted towards the GWP of scCO_2 MWF. Figure 5 shows the GHG accounting for the ammonia plant and the manufacturing facility using scCO_2 MWF. The GHG emissions in Scopes 0, 2, and 3 of the manufacturing facility add up to the GWP potential of scCO_2 MWF (5114 kg CO_2 eq.). Additionally, since spent scCO_2 MWF only consists of CO_2 and trace quantities of lubricant, both of which are non-toxic substances requiring no additional treatment, the end-of-life impacts from the use of scCO_2 MWF

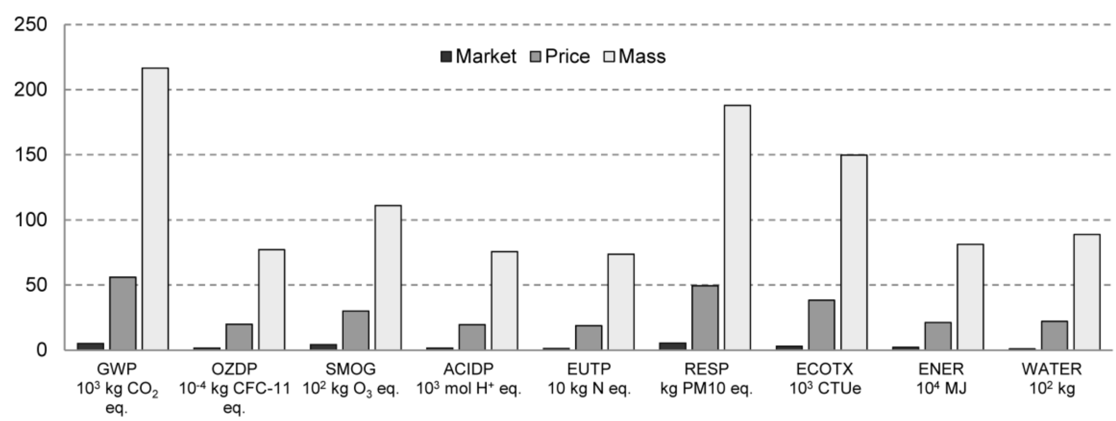


Figure 3: Comparison of different allocation methods for calculating the life cycle environmental impacts of scCO_2 MWF.

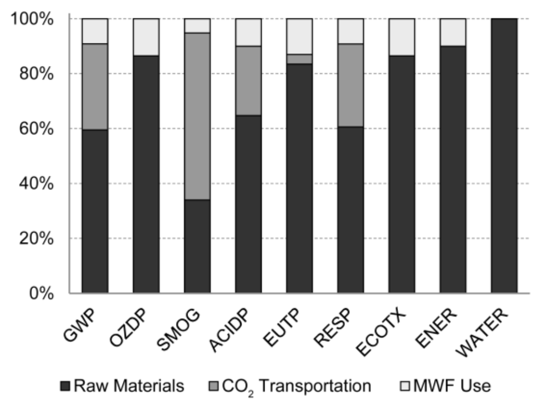


Figure 4: Breakdown of $scCO_2$ MWF environmental impacts by various stages in its life cycle. No significant end-of-life impacts observed for $scCO_2$ MWF.

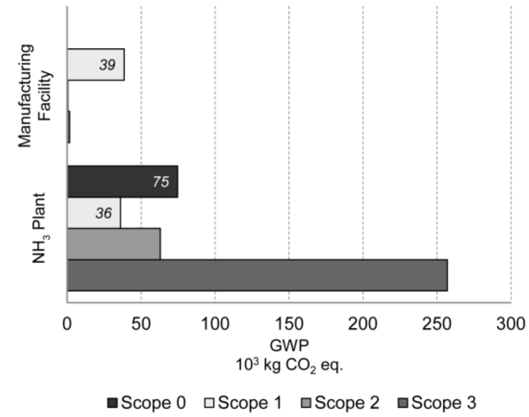


Figure 5: Application of the new GHG accounting method to the ammonia plant (CO_2 generator) and manufacturing facility (CO_2 emitter). All the CO_2 generated at the ammonia plant (Scope 0) is accounted for by the CO_2 emitted (Scope 1) at the plant and the manufacturing facility.

are insignificant.

Figure 6 compares the environmental impacts from $scCO_2$ MWF with high pressure aqueous MWF and LN_2 under the nominal operating conditions shown in Table 1. It is assumed that the aqueous MWFs are recycled weekly and disposed twice a year after proper primary, secondary and tertiary treatment of the spent MWF. The impacts shown for all MWFs do not include credits from the displaced conventional aqueous MWF end use. Avoided impacts from conventional aqueous MWFs, which are identical for all three MWFs are instead shown separately. These impacts should be subtracted from the impacts of each substitute MWF to estimate the marginal environmental impacts from the use of that substitute MWF.

It is observed that high pressure aqueous MWF has more than three times the impact of $scCO_2$ MWF in all categories. Most of the increased impact comes from the higher energy required to pressurize the water to about 11 MPa. The equipment, labor, and environmental compliance costs, as well as operator health and safety concerns associated with operating and maintaining conventional aqueous MWF systems still exist for high pressure aqueous MWF as they do for conventional aqueous MWF systems. While the analysis assumes that spent aqueous MWFs are properly treated before being discharged into the environment, this may not always be the case due the lack of specific regulations for MWFs. If untreated spent MWFs are released into the environment, they lead to high level of nutrient loading, human toxicity and ecotoxicity due to the presence of oils, biocides, and heavy metals.

Table 1: Values of key input parameters used in the LCA

PARAMETER	VALUE	UNITS
CO_2 flow rate	16	kg/hr
Vegetable oil flow rate	40	ml/hr
CO_2 Transportation Distance	250	km
Aq. MWF flow rate	1134	kg/hr
High pressure aq. MWF flow rate	3000	kg/hr
Aq. MWF sump size	100	gal
LN_2 flowrate	20	kg/hr
LN_2 Transportation Distance	925	km

LN_2 is produced using cryogenic air separation, which is an energy intensive process. This leads to higher environmental impacts compared with the other alternative MWFs. Transportation emissions for LN_2 are roughly 35% more than transportation emissions for CO_2, but the overall impacts are dominated by production of LN_2, and are thus strongly correlated with the flow rate of LN_2 MWF. The LN_2 MWF was assumed to be running without a lubricant.

It is important to differentiate and examine the environmental impacts of each MWF system from a qualitative perspective, as well as the quantitative perspective provided in Figure 6. For instance, global warming and ozone depletion are global impacts that have an adverse effect on the ecosystems worldwide regardless of the location of the emission source. Smog formation, acidification, eutrophication and ecotoxicity are more regional impacts. Even within each of these regional impacts, there is a qualitative difference between 1kg of pollutant emissions coming from a source such as an ammonia plant or a power plant that may be far away from populous areas, and 1 kg of the same pollutant emission coming from a source such as a transportation truck which causes a more localized impact on the air, water and soil quality. There could thus be a tradeoff between regional air quality and operator health and safety when selecting a MWF system.

The absolute value of the emissions should also be taken into account while assessing the relevance of a particular environmental impact. For instance the GHG emissions from $scCO_2$ MWF are comparable to an average person's annual personal driving GHG emissions, but all of the MWF systems considered here have several hundred times the average person's acidification or photochemical smog footprint. The decision to select a particular alternative MWF system thus has to put the quantitative LCA results in the context of a qualitative assessment of global, regional and human health impacts relative to the existing levels of pollution. These considerations should be made on a case-by-case basis beginning with the LCA results and approch provided here.

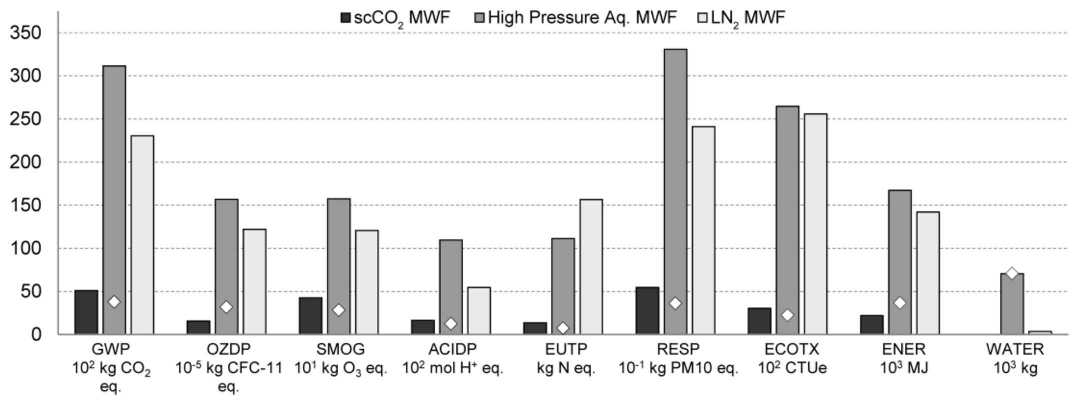


Figure 6: Life cycle environmental impacts of $scCO_2$, high pressure aqueous, and liquid nitrogen MWFs without displaced end use credit. Points along the high pressure aqueous MWF data represent values for conventional aqueous MWFs (displaced end use).

4. CONCLUSION

A market based allocation method consistent with consequential life cycle assessment frameworks is proposed for quantifying the market driven emissions associated with the use of recovered carbon dioxide in sustainable manufacturing applications. A greenhouse gas accounting method is also proposed that distinguishes between greenhouse gas generation and emission, thus

- creating a framework to assess and account for the true environmental impacts associated with utilizing recovered CO_2 to displace manufacturing processes that involve hazardous and energy intensive substances, and,
- eliminating barriers to the use of recovered CO_2 in such applications owing to previous problems of perception related to the use of mass-based and price-based allocation methods in assessing the environmental burdens of systems based on recovered CO_2 .

The approach is applied to estimate marginal emissions and environmental impacts from using CO_2 generated from an ammonia plant in a supercritical CO_2 metalworking fluid used at a manufacturing facility, while displacing the costly aqueous metalworking fluids that are harmful to operator health. The results indicate significant improvements machining productivity tool life and operator exposures may also come along with significant environmental improvements. Future work should focus on considering other end-use applications as well as understanding the local environmental impacts of recovered CO_2 systems.

5. REFERENCES

[1] Subramaniam B., Rajewski R.A., Snavely K., (1997), “Pharmaceutical Processing with Supercritical Carbon Dioxide”, *J Pharm Sci*. *86* (8), pp. 885-890.

[2] Kiran E., Debenedetti P.G., Peters C.J., (2000), “Supercritical Fluids: Fundamentals and Applications”, Kluwer Academic Publishers, *AA Dordrecht*, The Netherlands.

[3] Weibel G.L., Ober C.K., (2003), “An Overview of Supercritical CO_2 Applications in Microelectronics Processing”, *Microelectron Eng. 65* (1-2), pp. 145-152.

[4] Raventos M., Duarte S., Alarcon R., (2002), “Application and Possibilities of Supercritical CO_2 Extraction in Food Processing Industry: An Overview”, *Food Sci Technol Int*. *8* (5), pp. 269-284.

[5] Clarens A.F., Hayes K.F., Skerlos S.J., (2006), “Feasibility of Metalworking Fluids Delivered in Supercritical Carbon Dioxide”, *J Manu Process*. *8* (1), pp. 47-53.

[6] Clarens A.F., Zimmerman J.B., Keoleian G.A., Hayes K.F., Skerlos S.J., (2008), “Comparison of Life Cycle Emissions and Energy Consumption for Environmentally Adapted Metalworking Fluid Systems”, *Environ Sci Technol*. *42* (22), pp. 8534-8540.

[7] Overcash M., Li. Y., Griffing E., Rice G., (2007), “A Life Cycle Inventory of Carbon Dioxide as a Solvent and Additive for Industry and in Products”, *J Chem Technol Biot*. *82* (11), 1023-1038.

[8] Ekvall T., Weidema B.P., (2004), “System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis”, *Int J Life Cycle Assessment*. *9* (3), pp. 161-171.

[9] WRI, “The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard”, *The World Resources Institute and World Business Council for Sustainable Development*, 2004.

[10] Cheng, C., Phipps, D., Alkhaddar, R.M., (2005), “Treatment of Spent Metalworking Fluids”, Water Res. *39* (17), pp. 4051-4063.

[11] Klocke, F., Eisenblätter, G., (1997), “Dry cutting”, *CIRP Ann Manu Tech. 46* (2), pp. 519– 526.

[12] Wang S., Clarens A.F., (2013), “Analytical Model of Metalworking Fluid Penetration into Flank Contact Zone in Orthogonal Cutting”, *J Manu Process*. *15* (1), pp. 41-50.

[13] Supekar S.D., Clarens A.F., Stephenson D.A., Skerlos S.J., (2012), “Performance of Supercritical Carbon Dioxide Sprays as Coolants and Lubricants in Representative Metalworking Operations”, *J Mater Process Tech*. 212 (12), pp. 2652-2658.

[14] Byers J.P. (2006), “Metalworking Fluids”, Taylor & Francis Publishers”, *CRC Press*, Boca Raton, Florida.

[15] Argonne National Laboratory, U.S. Department of Energy, GREET Database Version 7837, 2013.

[16] PRé Consultant, SimaPro 7.3.3 LCA software, Amersfoort, The Netherlands, 2012.

[17] National Renewable Energy Laboratory, U.S. LCI Database, 2009.

GCSM 11th Global Conference on Sustainable Manufacturing
2013 23rd - 25th September Berlin - Germany

10.6 Sustainable increase of overhead productivity due to cyber-physical-systems

G. Schuh, T. Potente, C. Wesch-Potente, A. Hauptvogel [1]

[1] Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Aachen, Germany

Abstract

The amount of information is increasing constantly because of a growing automation in manufacturing processes and an increasing application of sensors. To handle this information in order to ensure sustainable decisions is the challenge in the future. Concurrently, the amount of decisions made by the management are increasing, which demands for an improvement of overhead productivity. This requires both the existing practical knowledge new technologies, which must be linked by matching software systems. The growing complexity of business processes will be configurable and controllable by the use of new assistance systems. Cyber-physical systems having characteristics such as ad-hoc networking, self-configuration and intelligent data processing will play a decisive role. This paper presents how current innovations can make an essential contribution to a further increase of overhead productivity by the support of collaboration and communication through cyber-physical systems.

Keywords:

Cyber-physical-systems, Optimization, Productivity, Sustainability

1 INTRODUCTION

Producing companies are facing the challenge to offer products matching individual customer demands at competitive prices [1]. At the same time the production is characterized by increasing market dynamics [2]. Hence, an adaptability of production systems is required, while assuring an efficient use of resources. Therefore, the effort and the complexity of planning, development and administration along the order fulfillment process increases. Indirect processes of manufacturing companies have been growing constantly and the need for knowledge workers and management staff rises. Today the support of these overhead functions must be focused to improve the overhead productivity. Thus, manufacturing processes will be more efficient in supporting producing companies to succeed on a global market.

Within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" current innovations are regarded to make a contribution to a further increase of overhead productivity by the support of collaboration and communication through cyber-physical systems.

2 INCREASING LABOUR PRODUCTIVITY IS THE CORE OF INDUSTRIAL DEVELOPMENT

The continuous increase in labor productivity is not only essential to high-wage countries it is the core of our industrial development and economic growth. In the last 20 years the annual increment of productivity (measured as gross domestic product GDP per person employed) in the countries of the OECD averaged 1,6 percent with tendency to sink, as shown in figure1 [3].

In the path of the industrialization three milestones of industrial revolution had a substantial impact on the increase of productivity.

- Availability of energy enables utilization of machines
- Economies of scale through division of labour
- Exponential growth in computing power enables automation of production

The development of the steam machine in the late 18th century marked the beginning of the first industrial revolution. As result the textile industry moved away from a decentralized production to a single production facility. The success was not driven by the plain revolutionary design, in fact it was the economic usability combined with a demand for a higher productivity. Due to the decentralization of production, many workers left their villages and moved to the city to find work at a factory. A former agrarian society changed to an industrial urbanized society [4].

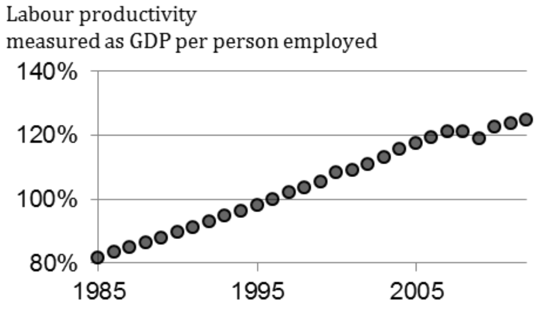


Figure 1: The development of labor productivity (OECD) [3].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

In the early 20th century the upcoming second industrial revolution laid the ground for a further increase in productivity. Henry Ford's introduction of the assembly line and Charles Taylor's scientific management enabled mass production of standardized goods, such as the Ford Model T [5]. Falling product prices and rising income lead to a rising consumption. Governmental regulations were passed to improve the working conditions and social issues. The second industrial revolution was enabled by the recognition that costs decrease if quantity rises.

The third industrial revolution was essentially a shift from mechanical and analogue electronic technologies towards digital technologies and is therefore sometimes also called the digital revolution. It began around 1980. One of its main results has been the automation of the production. The third industrial revolution has been enabled by the invention of digital computers. Their increase in processing power can be described by Moore's Law, which dates back to 1965. As it is displayed in figure 2, Moore's Law states that the number of transistors on a given chip can be doubled every two years [6].

Although the period is frequently quoted as 18 month in present times the law has been accepted until today. The improving chip performance is ensured by a higher number of transistors on integrated circuits. The increasing performance goes hand in hand with a simultaneous reduction in price. Moreover the increase in performance allows to solve problems, that couldn't be solved before. Today for example the implementation of data mining in web search engines is no longer a problem. At the same time the price reduction and performance improvement ensure that the application of such systems is possible in new areas. With the use of these systems additional data is created, which form a digital infrastructure that enables the step in further innovation [9].

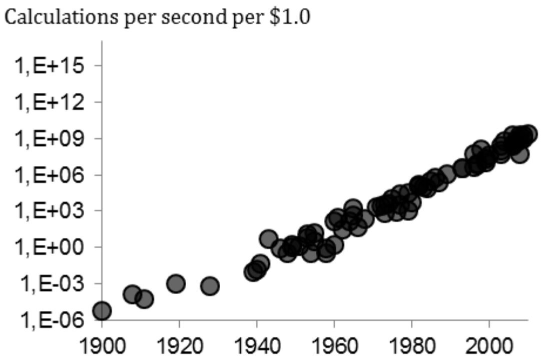


Figure 2: exponential growth of computing power: Moore's Law [7, 8].

According to Kagermann the fourth industrial revolution has just started [10]. New technologies enable a collaborative productivity, from which production and the whole economy might benefit in a way that new increases in productivity can be reached. In order to take advantage of this new development a description analogue to Moore's Law is essential. In the following chapter we deduce a trajectory, which describes the development of collaborative productivity as a result of this fourth revolution.

3 INDUSTRIALIZATION OF OVERHEAD THROUGH COLLABORATIVE PRODUCTIVITY

3.1 The 4th industrial revolution and industrialization of overhead

Collaborative productivity is defined by three types of collaboration and communication: between people, between people and smart devices (Human–computer Interaction, HCI) and between smart devices themselves (Machine to machine, M2M). The main prerequisite for these information exchanges is the internet. In 2008, the things connected to the internet exceeded the human population on earth [11]. This progress is partially driven by the rising popularity of smartphones and their ability to access the internet irrespective of the place and time. Therefore it's possible to instantly gain or provide information. Social networks like Facebook benefit from this development as they allow people to connect with each other. Consequently smart devices use the internet or local networks to communicate with one another, whether there's direct human interaction present or not. While the first three revolutions had a strong focus on the shop floor we are now facing the opportunity to industrialize business processes and overhead. Most companies focus on improving production and logistics while disregarding the potentials in their indirect departments (see figure 3).

In order to tap the potentials and increase the productivity in these areas, companies have to industrialize their business processes and overhead focusing on collaboration and communication. The improvement of the work performance, especially facilitating processes and assisting decisions can be supported by cyber-physical systems. Cyber-physical systems can be considered as a composition of embedded systems, real physical systems and sensor systems [12]. These objects can communicate via internet. An object can be both man and machine [13]. The real physical world and the virtual world, the "cyberspace", are completely connected with each other [10].

The impact of the current developments can be illustrated by three examples:

- Researchers at the University of Southern California took four years: 1986, 1993, 2000 and 2007 and extrapolated numbers from roughly 1,100 sources of information [14]. They discovered that in 2002, digital data storage surpassed non-digital for the first time and by 2007, 94 percent of all information on the planet was already in digital form.
- A study of Accenture shows how consumer technology is changing the modern workplace [15]. Employees are demanding the right to use their own smartphones and tablets. They feel more productive using their personal IT. Executives can not ignore this fundamental change anymore even though they have no adequate answer to manage this situation yet. 23% of employees use their personal devices at work regularly and about the same amount of employees would even be willing to defray the costs. 44% are dissatisfied with the devices and software applications provided by their company [15].
- In a freestyle chess tournament in 2005 hosted by Playchess.com anyone could compete, even teams of people or people with computer [16]. Surprisingly not the grandmaster with a state of the art computer or the super-computer won but a group of amateurs using three computers at the same time. They managed to combine

human strategic guidance with tactical acuity of a computer in the best way.

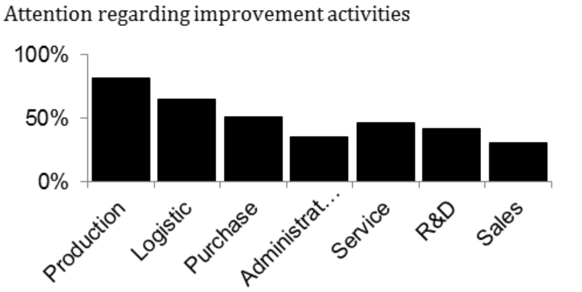


Figure 3: Results of a survey from 2011 of WZL RWTH Aachen University regarding production systems in over 80 companies.

3.2 Approach of predicting the industrialization of overhead

Due to cyber-physical-systems and their impact on collaboration we expect the possibility of a strong increase of productivity in indirect departments that needs to be faced. In this chapter we will introduce an approach for predicting this industrialization of overhead. In the same time the presented approach gives details on how to face these changes.

The core idea of the approach is that in the future more and more management activities will be supported and consulted by information technology devices, which are cyber-physical-systems. Management, indirect employees and all kind of brain workers will spend less time with gathering information or doing routine activities. Instead they will be disburdened by smart devices that allow data access in real time and high resolution and autonomous execution of routine tasks.

To predict the industrialization of overhead, the presented approach takes four main aspects into account.

- The increasing performance of smart devices, software and hardware [17]
- The increasing number of smart devices including infrastructure [18]
- The friction or efficiency of the interfaces (data-software, software-software, human-software)
- The management qualifications of the employees, which we keep constant in this approach.

We choose to keep the management qualifications constant in this first approach in order to simplify the model and focus on the main implications. However we assume, that the qualifications of employees will rise due to the interaction the interaction with these smart devices and the systematic aggregation of information and the succeeding learning and experiencing.

As a conclusion of the chess tournament Geshe deduced an equation to explain the unexpected outcome [16]. This equation combined with an equation of Hilbert is used to calculate the increase of overhead productivity (see Table 1) [17].

Table 1: calculation of overhead productivity

$\Delta_a = \frac{a_i}{a_{i-1}} - 1$	
$a_i = h_i \frac{c_i}{(1+f_i)}$	$h_i = const.$
	$c_i = c_{i-1} + (c_{i-1} \times (p_h + p_s + n))$
	$f_i = f_{i-1} \times (1 - r)$

Variables

p_h	4%/a	incr. of performance of devices, hardware
p_s	2%/a	incr. of performance of devices, software
n	2%/a	incr. of number of devices, infrastructure
c	(p_n, p_s, n)	computer power
h	const.	Management power
f_0	0,5	friction of human-computer interaction
r	5%/a	reduction of friction per year
a	(h, c, f)	analytic management power
Δ_a	1/a	incr. of overhead productivity per yr.
i		year

As a result of the equation figure 4 displays the expected curve of the increase of overhead productivity in the following years. The development is based on the assumptions shown in the variable list (see Table 1).

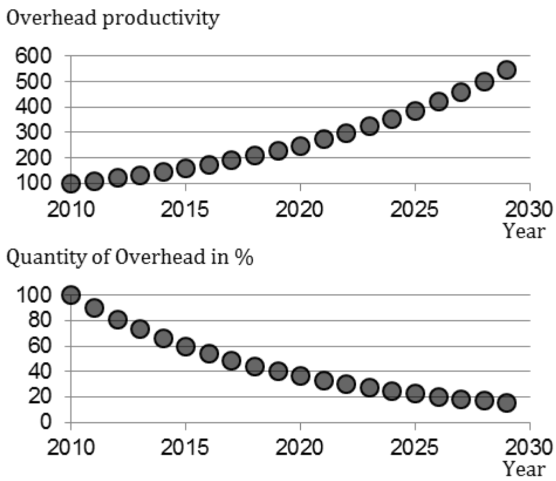


Figure 4: Increase of overhead productivity in the following years.

The assumptions from Hilbert (concerning the variables p_h, p_s and n), which are based on a static system state, have been adapted to meet the reality in companies. Furthermore Hilbert calculates with higher values [17]. We reduced these values according to the average life cycle of devices in companies. The result is a rather conservative gradient of the curve. The friction of human-computer interaction is a first assumption based on experiences and is currently being validated in an on-going research project.

3.3 Preconditions for the increase of productivity

To reach the described increase of productivity in indirect departments of a producing company, the following innovations are necessary:

- technological support for communication
- reduction of friction between management and IT
- semantic models to override the heterogeneous IT-world

In the Cluster of Excellence nine projects are inventing technologies to support the described development. One of them is AixViPMaP, a project that develops a platform to integrate material and process simulation to overcome semantic problems in the product and process development process [19].

4 CONCLUSION AND FURTHER RESEARCH

An increase of productivity of overhead is essential for companies in high-wage countries as well as emerging economies. The analytical skills of human management power will rise through the intense interaction with new hard- and software applications. Thus, the complexity in planning production processes can be handled more efficiently and reliably. The results are ideally planned manufacturing processes with reduced planning costs. Applied systems and their solutions will be more transparent and the trust in these systems will rise.

Nevertheless the described development and its implications will call for further research in production management as well as in human-machine-interaction to further increase the productivity of overhead.

5 ACKNOWLEDGMENTS

The authors would like to thank the German Research Foundation DFG for the kind support within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries".

6 REFERENCES

[1] Brecher, C., 2012, Integrative Production Technology for High-Wage Countries, Springer, Berlin, pp. 21-23.

[2] Wiendahl, H.-P., ElMaraghy, H., Nyhuis, P., Zäh, M., Wiendahl, H.-H., Duffie, N., Brieke, M., 2007, Changeable Manufacturing—Classification, Design and Operation, Annals of the CIRP, 56/2, pp.783–809.

[3] OECD, 2012, Economic Outlook, Volume 2012 Issue 2 - No. 92, http://www.oecd.org/statistics/(05.01.2013)

[4] Robert, C., 2006, The British Industrial Revolution in Global Perspective: How Commerce Created The Industrial Revolution and Modern Economic Growth, Nuffield College, Oxford.

[5] The Economist, 2012, The third industrial revolution, The digitisation of manufacturing will transform the way goods are made—and change the politics of jobs too, Apr 21st 2012, www.economist.com/node/21553017

[6] Moore, G., 1965, Cramming more components onto integrated circuits, Electronics Magazine, p. 4.

[7] Kurzweil R., 2005, The singularity is near: When Humans Transcend Biology, Viking Press, p. 70

[8] Borkar, S., 2000, Obeying Moore's Law Beyond 0.18 Micron, Proc. ASIC/SOC Conference, 2000. Proceedings. 13th Annual IEEE International, IEEE, pp:26-31.

[9] Broy, M., 2010, Cyber-Physical Systems, Springer, Berlin, pp. 17-32.

[10] Kagermann, H., 2012, Die vierte industrielle Revolution, Zukunftsmanager, 3, pp. 4-8.

[11] CISCO, 2012, The Internet of Things, http://blogs.cisco.com.

[12] Rajkumar, R., Insup, L., Lui, S., Stankovic, J., 2010, Cyberphysical systems: The next computing revolution, Proceedings of Design Automation Conference (DAC) 2010 47th ACM/IEEE, VDE, pp. 731-736.

[13] Vogel-Heuser, B., Bayrak, G., Frank, U., 2011, Agenda CPS-Szenario smart factory, Erhöhte Verfügbarkeit und transparente Produktion, Kassel Univ. Press, pp. 6-21.

[14] Vastag B., 2011, Exabytes: Documenting the 'digital age' and huge growth in computing capacity, http://www.washingtonpost.com/wp-dyn/content/article/2011/02/10/AR2011021004916.html (05.01.2013)

[15] Harris, J. G., Ives, B., Junglas, I., 2011, The Genie Is Out of the Bottle: Managing the Infiltration of Consumer IT Into the Workforce, http://www.accenture.com/us-en/Pages/insight-managing-infiltration-consumer-it-workforce.aspx

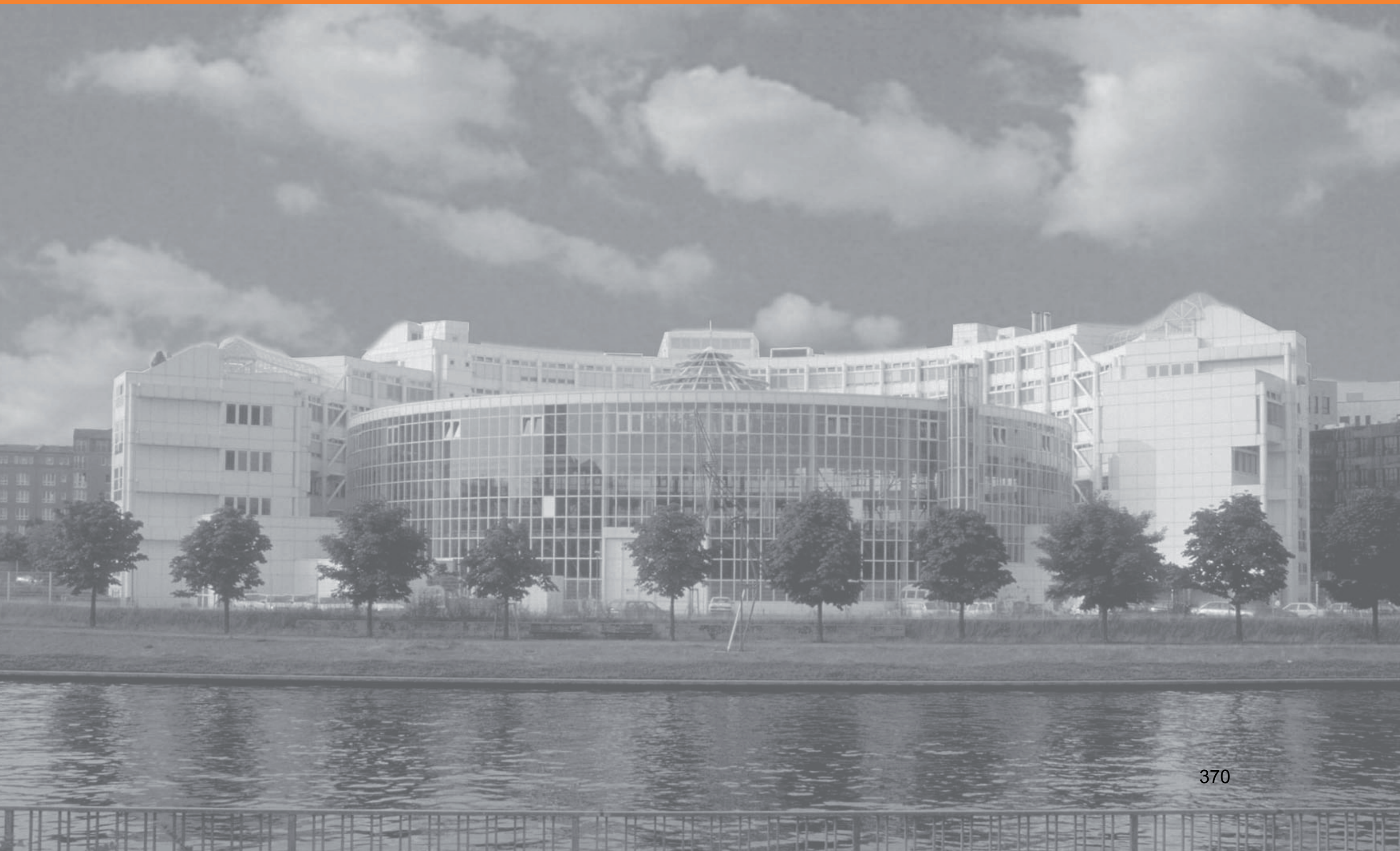
[16] Gesher A., 2010, Friction in Human-Computer Symbiosis: Kasparov on Chess, http://www.palantir.com/2010/03/friction-in-human-computer-symbiosis-kasparov-on-chess/ (05.01.2013)

[17] Hilbert, M., 2011, What Drives the Global Growth of Information?, Ideas Economy: Information 2011, Santa Clara, California, USA, June 7th-8th 2011.

[18] Lindeman, T., Vastag, B., 2013, Rise of the digital information age, The Washington Post, http://www.washingtonpost.com/wp-dyn/content/ graphic/2011/02/11/GR2011021100614.html

[19] Schmitz G.J., Prahl U., 2012, Integrative Computational Materials Engineering – Concepts and Applications of a Modular Simulation Platform, Wiley

Session 11
Energy Efficiency



11.1 Fostering energy efficiency by way of a techno-economic framework

M. Putz [1], U. Götze [2], J. Stoldt [1], E. Franz [1]

[1] Fraunhofer Institute for Machine Tools and Forming Technology, Chemnitz, Germany

[2] Chair of Management Accounting and Control, Chemnitz University of Technology, Chemnitz, Germany

Abstract

Aiming for a more benign approach to manufacturing, new technological and logistical approaches to energy sensitive production control have been developed. However, practical experience shows that these are or will usually not be implemented due to unclear or conflicting objectives from the technical and the economic side. A prominent example for this is buffers within production systems. While these should be avoided or at least minimised in order to decrease costs and investments, they may allow for the temporary transfer of production equipment into less energy consuming operation states. This paper reports on joint efforts to reduce interface issues by integrating technical and economic decision making into a consistent procedural framework. Exemplary for its potential application, a specific approach to energy sensitive production control, as well as fundamentals for both a technical and an economical evaluation thereof are presented.

Keywords:

Energy efficiency; Economics; Production control

1 INTRODUCTION

Energy and resource efficiency have already become a predominant aspect in the industry around the world and will further increase in importance. Production control will no longer only be concerned with output, time, quality, and direct costs but will be sensitive and responsive to the actual energy and resource supply as well as consumption in order to contribute to the competitiveness of companies better still. The recent predominance of energy control in production processes, e.g. in car production, is based on advanced technical and logistic approaches, and solutions in both single process steps and complex process chains. Aside of the technical options and point of view, production control is an important matter for economic targets and decision making. Systematically integrating both points of view (technical and economic) may avoid interface problems during implementation and optimisation, which still appear in practice, thereby providing significant advantages. A first task toward this goal could be to improve the interaction through the combination of technical and economic based planning, as well as the development of novel methods, scenarios, and well-proven approaches.

Planning and controlling manufacturing sites is a complex and interdisciplinary task that various stakeholders take an interest in. A significant problem in this regard is that the goals and focus of the concerned decision makers from individual departments diverge. Accordingly, they utilise distinct key performance indicators (KPI) in order to assess the effectiveness of measures and the performance of the production system [1]. Linking these to actual system parameters, however, is difficult; interface-related losses sometimes complicate an optimisation. While various publications discuss methods and approaches to increase energy and resource efficiency [2] few pay attention to the interdisciplinary nature of their implementation. Herrmann et al. suggested an approach which aims to integrate the ecological and the economic process model [2]. However, this work is strongly focussed on technical solutions and pays little attention to the fundamental economics involved in this field and the interaction of economists and technical adept personnel. With respect to levels of manufacturing activity defined by Duflou et al. (see [2]) it should be noted that the interests of concerned stakeholders vary. For instance, measures on the device level frequently do not concern logistic planners; optimisations on the line level will almost certainly concern them. This paper focuses on the line as well as facility level and describes how a novel approach to energy sensitive production control can be implemented and evaluated using a framework that integrates the technical and the economic view.

A review of recent publications shows that several approaches for improving the resource efficiency in manufacturing by altering the production planning and control have been developed [4-6]. These are usually intended for a narrowly defined type of production system or situation. The approach presented in this paper aims to join the benefits of already established production control strategies with new concepts of equipment control, i.e. the ability to remotely shut down individual subsystems and machines, and thus provide a solution applicable in a variety of production systems. In order to establish a holistic basis for its implementation – including both the technical and the economic view – a framework based on the Plan-Do-Check-Act (PDCA) methodology is presented in section 3 after some context for its development has been provided in the following section.

2 CONTEXT AND SCOPE OF THE PRESENTED WORK

This particular work is the result of the on-going effort of the interdisciplinary research project "Energy-sensitive Planning and Control in Factory Operations" (eniPROD-LF2), which is part of the Cluster of Excellence „Energy-Efficient Product and Process Innovations in Production Engineering“ (eniPROD®). The objective of this project is to identify, analyse and, where appropriate, develop or advance

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

strategies for energy sensitive production planning and control in a manner appropriate for the analysed object. In the process, energy efficiency shall be established as a target variable alongside the traditional cost and performance targets (inventory, throughput time, capacity utilisation, scheduling reliability) within the framework of factory operations.

Aiming to provide solutions which further the co-operation of all stakeholders in companies, an interdisciplinary research team (figure 1) was composed of specialists in controlling (MAC, Chair of Management Accounting and Controlling), factory planning (FPL, Chair of Factory Planning and Factory Management), and mathematics (ADM, Chair of Algorithmic and Discrete Mathematics) from the Chemnitz University of Technology and researchers from the Fraunhofer Institute for Machine Tools and Forming Technology (IWU). These participants analyse the tasks, methods, and algorithms in production and logistics control to derive energy-relevant strategies. Experts of the “Virtual Reality Center Production Engineering” (VRCP) aim to develop new energy-related AR-based visualisation and interaction techniques, in order to support operators charged with control tasks. Furthermore, psychologists study (PSY, Chair of Personality Psychology and Assessment) the human factor in control processes (e.g. motivational measures, knowledge distribution), specifically addressing the need for and the design of decision-making support in case of parameter uncertainty or conflicts of objectives.

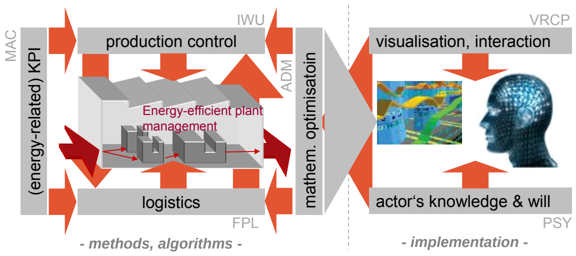


Figure 1: The eniPROD-LF2 approach.

The hereafter presented approach picks up these ideas of eniPROD-LF2 and joins them into a single framework. This interdisciplinary approach will help to significantly improve the identification and exploitation of efficiency potentials.

3 IDENTIFYING AND EXPLOITING EFFICIENCY POTENTIALS

It has already been mentioned that different departments of a company use distinct KPI. Those with a technical focus usually work with non-monetary figures that can either be measured directly or derived from the afore-mentioned, e.g. the reject rate. On the other hand, economic experts prefer KPI that are closely related to the evaluation of the economic success of a company and the customer-related processes, such as costs per unit.

Aiming to exploit efficiency potentials – thus affecting the various KPI – parameters that can be varied in order to influence the production system’s behaviour need to be identified. Their character, purpose and borders are usually defined by production planners. Connections with individual KPI, however, need to be determined in order to support multi-criteria decision making. For this purpose, the Plan-Do-Check-Act (PDCA) methodology has been adapted as depicted in figure 2. Its centre features the differing technical/logistic and economic view, as well as the parameters and their connection to the individual views. This concept of multiple views is both the reason and the basis for the hereafter described framework.

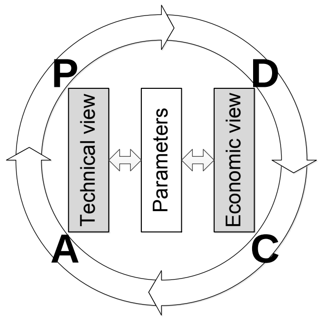


Figure 2: PDCA cycle adapted to identify and exploit efficiency potential.

The PDCA cycle – also known as Deming cycle – is a management method which was predominantly developed for identifying, developing and implementing quality measures [7]. Starting from an identified problem, measures are derived and implemented in a process of continuous improvement within four steps: “Plan”, “Do”, “Check”, and “Act”. The main advantage of the methodology is that it makes use of interdisciplinary teams (here: engineers and economists) for the holistic examination of problems and the identification of viable solutions.

In order to adapt this methodology for the identification and exploitation of efficiency potentials in manufacturing, the content of the individual steps of the PDCA cycle has to be altered. Figure 3 depicts an overview of the new process; a comprehensive description is presented thereafter.

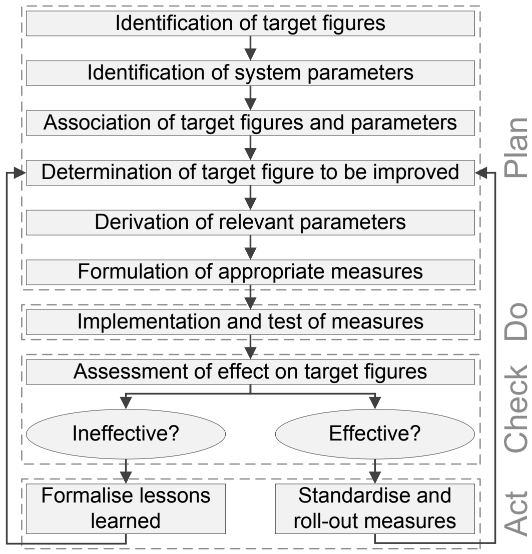


Figure 3: Process steps of the new PDCA cycle.

The step “Plan” aims for the identification as well as the determination of target figures from a technical/logistic and economic view. Each identified target figure has to be associated with related parameters of the production system. Based on the intended optimisation for a certain target figure all relevant parameters have to be identified. Their qualitative impact on the systems performance can be estimated taking the team's interdisciplinary know-how into consideration. Accordingly, specific measures, i.e. changes to the parameters, have to be devised.

Testing the effect of the devised measures deduced from the identified connections between parameters and target figures is the aim of the step "Do". Different scenarios should be examined in experiments, which are planned according to established design of experiments (DoE) methods. The actual testing process can be conducted in either a real or a virtual (i.e. simulation model [e.g. 8]) manufacturing system. Especially, the latter can minimise the necessary effort as identified measures can be implemented and analysed in a discrete-event simulation system (if the model is accurate!), not influencing on-going production.

Results from the previous step "Do" will be assessed in the step "Check" in order to determine how effective the devised measures are. For this purpose, aspects from both the technical/logistic and the economic view need to be considered conjointly. In case of a negative decision being reached, i.e. the measure has to be deemed ineffective, the findings of the step "Check" can be used to devise new measures and should therefore be preserved.

The step "Act" is concerned with acting upon the result of the previous step. Similar to the original PDCA methodology, measures that have been proven effective should first be standardised and then rolled out to the inspected production system and – if possible – to similar production systems. This approach further increases the efficiency of the described framework because lessons learned can be transferred or referenced in another iteration of the PDCA cycle with little effort. On the other hand, if measures have not been effective a new iteration has to commence in order to devise measures that eventually satisfy the optimisation aims and exploit efficiency potentials.

These explanations show that the proposed framework is meant to provide a systematic approach to the interdisciplinary work of various departments. How experts from either the technical/logistic or the economic side go about optimising the system in question is highly dependent on the actual task, i.e. increasing the energy efficiency of a system will typically require different tasks than increasing its degree of automation. Accordingly, the following two sections discuss – based on a case study – methods and approaches which can be used within this framework in order to increase the energy efficiency of a manufacturing site. More specifically, the fourth section focuses on the technical/logistic view, introducing a novel approach to energy sensitive production control and discussing how it can be examined by means of simulation technology. Section 5 elaborates an approach to the economic assessment of the simulation results.

4 CONFIGURING ENERGY SENSITIVE PRODUCTION CONTROL STRATEGIES

An important step in the implementation and optimisation of novel as well as established production control strategies is the (re-)configuration of parameters in order to reach a predefined system performance. Depending on the system's complexity, this is a difficult task which can comprise a multitude of different methods, such as heuristics, simulation, or trial and error. Each of these has certain limits and benefits, although especially simulation techniques gained noticeable acceptance in various industrial sectors. In this regard, the instrument of choice for discrete production processes is the discrete-event simulation [9]. Hereafter, a novel approach to energy sensitive production control and the configuration thereof are elaborated.

The object of study is a section of an exemplary car body production facility where attachment parts (i.e. doors, bonnet, etc.) are assembled and mounted to the otherwise complete frame. It consists of four work stations (WS) where – in order of the material flow – the front doors (FD) and rear doors (RD) for car body variants with five doors, the bonnet and the tailgate, the front doors for variants with three doors (left and right assembled separately), and the wings (left and right produced separately) are mounted. Each work station is supplied by two subsystems (see figure 4) which contain between one and five work groups and are connected via conveyors as well as buffers. The work groups are complex and highly automated robot cells. The four work stations are followed by a so called "light tunnel" where all car bodies are inspected for imperfections.

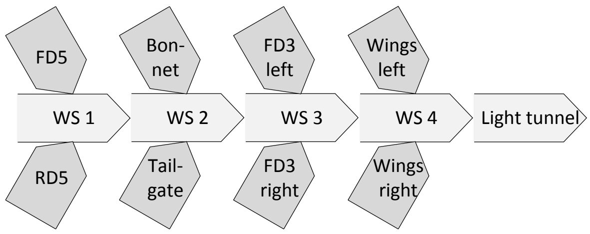


Figure 4: Structure of the exemplary production facility.

This production system has been modelled using Siemens Tecnomatix Plant Simulation. Since this software only allows for the study of material flows, a generic energy-enhancement module – eniBRIC – has been developed to provide additional capabilities [10,11]. Each regarded entity has to be complemented with an instance of eniBRIC which then needs to be parameterised. Energy-relevant parameters include available operation states, required and provided media as well as media consumption in each of the states, the time required for state transitions, and flags influencing the behaviour of individual enhancement module instances. Switching between operation states is possible through standardised interfaces but has to be triggered actively by an additional controlling instance. Furthermore, a configuration and a data collection and evaluation module have been developed but these only have to be instantiated once. Media-supplier-consumer-relationships have to be defined in a central table which is part of the configuration module, along with global setting templates for the flags. Instances of eniBRIC communicate their media demand amongst one another and to the data collection and evaluation module. The latter gathers and aggregates data during simulation time and can visualise or export it according to the users' requirements [11].

Using the VDA Automotive Toolkit, each work group, work station, conveyor, and buffer has been modelled as a single simulation object. All of these, except for the buffers, have been enhanced with eniBRIC. Regarded media include power (400 V and 690 V), laser light, pressured air (6 bar and 12 bar), lighting, smoulder suction, ventilation, cold water, and cooling water; suppliers for these media have been instantiated and configured. Additionally, methods allowing for an energy sensitive equipment control have been implemented. In particular, it is possible to either pause the entire system, or shutdown and start-up individual subsystems [11].

This model has been used to implement and examine a novel approach to energy sensitive production control which is based on the established Kanban principle. This new eniKanban approach enhances the fundamental Kanban procedure with additional rules for powering equipment on or off whenever the buffer after a controlled subsystem reaches a certain thresholds [12]. The basic idea is to shut down and start up equipment as soon as the amount of parts available in decoupling buffers is either sufficient or getting too low. Naturally, this can only work if the controlled subsystem works faster than the subsequent one so that the buffer gradually fills. Suggesting that the cycle time of subsystems is constant, the parameters for this approach are the buffer capacity and the safety stock. The difference between these two ("shutdown difference") also determines the least time the controlled subsystem may cease to produce.

In order to study their effect on technical/logistic and economic KPI – and thus provide indicators for the configuration –, a number of simulation experiments (each with a duration of 180 days and 50 unique observations) has been made. A preliminary investigation comprised of six experiments and focussed on the effect of the safety stock which determines when equipment should be started up again. For this purpose, the buffer capacity was set to 40 pieces and the safety stock was varied from 15 to 35 in steps of 5. An additional experiment was conducted in order to compare eniKanban with a classic Kanban production control strategy. The general findings in these experiments were that the amount of energy required per car body can be reduced considerably (up to 15% in this study) using eniKanban and that an increased safety stock tends to improve the systems overall output due to fewer supply shortages.

Further 24 experiments aimed to examine how the KPIs are affected by a variation of the buffer capacity. For this purpose, four values for the safety stock were chosen based on the previous observations and the buffer capacity was then varied in six steps so that the "shutdown difference" ranged from 5 to 30. The results made clear that it is possible to achieve an output with eniKanban that compares to the output with regular Kanban, however, this comes at the price of increasing the average stock. Interestingly enough, the amount of energy required per car body remains almost unchanged despite the parameter variation when eniKanban is used. Figure 5 depicts the average output of car bodies for the four examined safety stock (SS) sizes.

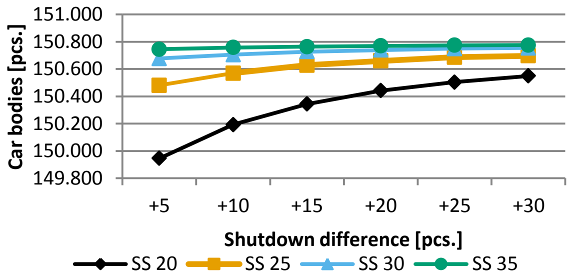


Figure 5: Average output dependent on the "shutdown difference".

The results from the conducted experiments show that energy sensitive production control can potentially be viable. However, the exact configuration needs to be decided upon considering all identified consequences (e.g. increased average stock, decreased energy consumption, etc.). Simulation experiments can be utilised to provide assistance and input data for the actual decision making process. The economic consequences caused by different configurations can be determined utilising the method introduced in the following section. Hence, the identification of an optimal configuration combining findings from the technical/logistic and the economic view can be supported.

5 ECONOMIC EVALUATION OF ENERGY SENSITIVE PRODUCTION STRATEGIES

The results of the simulation utilising the eniKanban method show that trade-offs concerning the achievable benefits in comparison with a "traditional" Kanban control exist. Compared to a "traditional" Kanban concept, the eniKanban control allows for a reduction of the energy consumption but it also implicates a certain decline of the output as well as raised stocks of inventory, depending on the exact configuration. Similarly, the choice of other alternative system parameters – here the size of the safety stocks and the maximum buffer capacities – will usually raise conflicts between these (and possibly other) company objectives.

To be able to evaluate the alternative actions and thereby systematically prepare a decision, an economic analysis lends itself to offer a deeper understanding of the respective economic consequences. In the scope of this analysis one solution is to formulate a multi-criteria problem which can be solved by determining, as well as weighting the relevant targets, assessing their fulfilment, and deriving a total utility score from the given data. Another approach is the formulation of a model indicating the (approximate) impact of alternative scenarios on the profit. Since profit is the central economic objective of companies, this paper discusses the latter solution. One potential approach for a profit-oriented evaluation of alternatives will be demonstrated using the example of the comparison between an eniKanban and a "traditional" Kanban control system. This method can also be used to compare individual parameter configurations.

In general, the profit (P) can be formulated as difference between revenues (R) and costs (C):

$$P = R - C \tag{1}$$

For the evaluation of the alternatives – "traditional" Kanban, and eniKanban –, the analysis can be limited to the variation of profit (ΔP) (and thereby also its components ΔR, and ΔC):

$$\Delta P = \Delta R - \Delta C \tag{2}$$

In case of the production system discussed in section 4, primarily the variation of the output ($\Delta output$), of the stock of inventory (Δinv), as well as of the energy consumption (ΔEC) determines the profitability of the alternatives. Their monetary consequences – the variation of contribution margin caused by alternate output quantities ($\Delta CM_{\Delta output}$), the variation of inventory costs (ΔC_{inv}), and the variation of energy costs (ΔC_e) – can be assessed using the following formula:

$$\Delta P = \Delta CM_{\Delta output} - \Delta C_{inv} - \Delta C_e \tag{3}$$

Further differentiating between the quantitative and monetary components of each item as well as types of inventory and energy carriers (with *cm* for contribution margin per unit, c_{inv} for inventory costs per average inventory unit, and c_e for energy cost per consumed energy or media unit, *j* as index of inventories (*j = 1…,J*), *i* as index of energy carrier units (*i = 1,…,I*)) leads to:

$$\Delta P = \Delta output \bullet cm - \sum_{j}^{J} \Delta inv_j \bullet c_{inv,j} - \sum_{i}^{I} \Delta EC_i \bullet c_{e,i} \quad (4)$$

The quantitative components of these values can be derived from the simulation or measurements in the real production system. In contrast, the contribution margin and the cost rates have to be investigated by an economic analysis [e.g. 13].

The contribution margin per output unit expresses the monetary effects of any variation of the output (per unit), e.g. as a consequence of using an eniKanban control instead of a "traditional" Kanban control. It follows:

$$cm = p - vc \quad (5)$$

Accordingly, the price (*p*) and the variable costs per unit (*vc*) have to be estimated for the basic alternative; thus, the effects on inventory and energy costs do not have to be taken into account here. In many cases price expectations will be available within companies. In this regard, the achievable price itself may depend on the output quantity. However, due to the slight extent of the output variation in the case study the effect can be considered insignificant. For the calculation of the variable costs per unit, methods of direct costing can be applied. Often, the corresponding values can be provided by the company's cost accounting system.

The average inventory costs result from the relevant costs of the physical stock-keeping ($c_{phys\ stock}$) as well as the cost of capital tie-up ($c_{capital}$), each of which is determined per inventory unit:

$$c_{inv} = c_{physstock} + c_{capital} \quad (6)$$

The computation of the relevant costs, i.e. the costs that vary depending on the stock of inventory, requires an analysis of the inventory system and the processes performed therein. In order to determine $c_{capital}$ the interest rate and the capital tie-up per inventory unit need to be identified. The latter is often assumed to correspond to the purchasing or manufacturing costs of an inventory unit, which may be calculated by means of a company's cost accounting system.

The costs per consumed unit of an energy carrier are highly dependent on the supply channel (make-or-buy, etc.). In many cases, the acquisition price of the purchased energy sources (p_{ext}) is complemented by costs for the internal supply (c_{int}), so that:

$$c_e = p_{ext} + c_{\text{int}} \quad (7)$$

The prices for externally procured energy carriers typically consist of fixed and variable price components, which are influenced by various factors, such as type of billing, duration of contract, or load balancing. Cost rates of internal energy supply can be investigated by means of a cost accounting system with energy-related specifications ("energy cost accounting" [14]).

Figure 6 provides an overview of the afore-described profit model, explains relationships between individual variables, and gives examples for influencing factors for these. It has to be noted, that the latter are incomplete and will have to be considered specifically for any regarded company.

Summarising, it can be noted, that it is possible to determine the impacts of the alternatives on the objective "profit" and, thereby, to identify profitable alternatives under consideration of the mentioned trade-offs. Amongst others, it can be analysed whether an eniKanban control is more economic than a "traditional" Kanban control in a specific production system. The avoidance of buffers propagated in many companies needs to be relativised, if aspects of energy efficiency are taken into account.

Admittedly, the concrete calculation of profit variations will raise methodological questions of detail and some simplifying assumptions concerning the cost components have to be made (e.g. of relevant costs including the isolation of costs, or linearity of costs depending on cost drivers). The explanatory power of results will depend on the validity of these assumptions. However, the analysis can be deepened and/or enlarged by including further cost items (e.g. the costs caused by a variation of the maximum buffer capacity), influencing factors and parameters (e.g. cycle times of process steps) or conducting sensitivity analyses in order to estimate the consequences of imperfect data. Nevertheless, the economic analysis can be applied in the Plan, Do and Check phases of a PDCA cycle contributing to a multi-perspective appraisal of policies and actions, promising various benefits.

6 SUMMARY AND OUTLOOK

A method for an integrated analysis, evaluation, and implementation of energy sensitive production control strategies was proposed, consisting of three elements: a PDCA cycle as a framework for systematically identifying and exploiting efficiency potentials, instruments for evaluating control strategies (here, a simulation model was used), and an economic assessment method which directly refers to the results of the technical evaluation. The presentation of the method against the background of the eniKanban control strategy and its configuration revealed the (energy saving) potentials as well as possible conflicts between different company objectives, implying the need for an economic evaluation.

The integrated method promises further benefits: It is expected to promote the discussion and operationalisation of objectives and their relevance, to assist the identification of need for action and the reconsideration of system boundaries and viable options. Additionally, the necessity of adjustments caused by a change of economically relevant factors within the PDCA cycle can be identified, and the company-wide acceptance of proposed measures strengthened, because the profitability of policies and actions have been proven in an economic analysis.

Thus, the integration of a technical/logistic and economic analysis and control is strongly recommended. However, the method proposed is still in an early phase of its life cycle. As one step, it is planned to enhance the simulation model by a corresponding module for economic analysis to investigate the variation of profit depending on the monetary components.

7 ACKNOWLEDGMENTS

The presented work summarises outcomes of the research projects InnoCaT® and eniPROD®. The pre-competetive joint research project "Innovation Alliance Green Car Body Technologies" is funded by the "Bundesministerium für Bildung und Forschung (BMBF)" (funding mark 02PO2700 ff) and supervised by "Projektträger Karlsruhe (PTKA)". The authors are responsible for the content of the publication. The Cluster of Excellence "Energy-Efficient Product and Process Innovation in Production Engineering" (eniPROD®) is funded by the European Union (European Regional Development Fund) and the Free State of Saxony.

8 REFERENCES

[1] Schuh, G., Arnoscht, J., Bohl, A., Nussbaum, C., 2012, Integrative assessment and configuration of production systems, Annals of the CIRP, 60/1, pp. 457-460.

[2] Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012, Towards energy and resource efficient manufacturing: A processes and systems approach, Annals of the CIRP, 61/2, pp. 587-609.

[3] Herrmann, C., Bergmann, L., Thiede, S., Zein, A., 2007, Framework for Integrated Analysis of Production Systems, Proc. of the 14th CIRP Conference on Life Cycle Engineering, Tokyo, pp. 195-200.

[4] Bruzzone, A. A. G., Anghinolfi, D., Paolucci, M., Tonelli, F., 2012, Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops, Annals of the CIRP, 61/1, pp. 459-462.

[5] Weinert, N., Chiotellis, S., Seliger, G., 2011, Methodology for planning and operating energy-efficient production systems, Annals of the CIRP, 60/1, pp. 41-44.

[6] Neugebauer, R., Putz, M., Schlegel, A., Langer, T., Franz, E., Lorenz, S., 2012, Energy-sensitive production control in mixed model manufacturing processes, Proc. of the 19th CIRP Conference on Life Cycle Engineering, Berkley, pp. 399-404.

[7] ISO 9001:2008, Quality management systems – Requirements.

[8] Herrmann, C., Thiede, S., Kara, S., Hesselbach, J., 2011, Energy oriented simulation of manufacturing systems – Concept and application, Annals of the CIRP, 60/1, pp. 45-48.

[9] Rose, O., März, L., 2011, Simulation, Simulation und Optimierung in Produktion und Logistik, Springer Verlag, pp. 13-20.

[10] Putz, M., Schlegel, A., Stoldt, J., Schwerma, C., Langer, T., 2013, Energy sensitive digital planning and simulation, Proc. of the International Conference on Competitive Manufacturing, Stellenbosch, pp. 365-370.

[11] Stoldt, J., Schlegel, A., Franz, E., Langer, T., Putz, M., 2013, Generic energy-enhancement module for consumption analysis of manufacturing processes in discrete event simulation, Proc. of the 20th CIRP Conference on Life Cycle Engineering, Singapore, pp. 165-170.

[12] Putz, M., Schlegel, A., Stoldt, J., Franz, E., Langer, T., Tisztl, M., 2012, A framework for energy-sensitive production control in MES, Proc. of the 14th International Conference on Modern Information Technology in the Innovation Processes of the Industrial Enterprises, Budapest, pp. 354-366.

[13] Hongren, C. T., Datar, S. M., Rajan, M., 2011, Cost Accounting, Prentice Hall.

[14] Bierer, A., Götze, U., 2012, Energy Cost Accounting: Conventional and Flow-oriented Approaches, Journal of Competitiveness, 4/2, pp. 128-144.

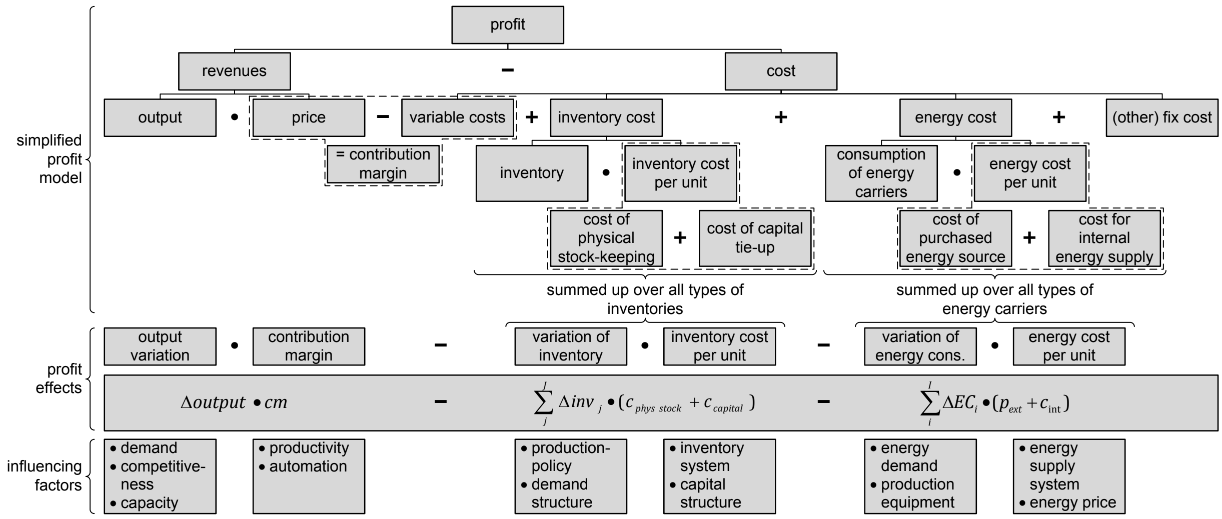


Figure 6: Overview of the described profit model.

11.2 Energy usage and efficiency in non-conventional micromachining

Paul Harris[1], Niall Aughney[2], Tom Whelan[3], Garret E. O'Donnell[1]

[1] Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, Ireland

[2] I2E2 Energy Research Centre, Collinstown Industrial Park, Leixlip, Kildare, Ireland

[3] Hewlett Packard Manufacturing, Liffey Park Technology Campus, Leixlip, Kildare, Ireland

Abstract

Energy efficiency is one of the main strategies adopted by companies to reduce their environmental impact. This paper presents some case studies on the energy consumption, both electrical power and compressed air, of abrasive jet and laser drill machines used in the production of printer inkjet cartridges. The study also examines the practical challenges involved in the implementation of energy reduction strategies in an industrial environment, and in particular the technical, economic and practical viability of energy saving solutions for in situ toolsets. The objective of the paper is therefore twofold: 1. To contribute to the understanding of energy use in non-conventional micro-machining, an important element of Life Cycle Inventory analysis and 2. To help researchers understand the difficulties in implementing energy efficiency measures, and in particular the role of risk as a barrier to energy savings.

Keywords:

Energy efficiency, Laser, Abrasive jet, Micromachining, Risk

1 INTRODUCTION

Energy efficiency is one aspect of sustainable manufacturing and is widely pursued by industrial entities as it allows for improvements to both economic and environmental performance. Over the last decade, there have been numerous studies into the energy usage of top level manufacturing plant [1], conventional manufacturing unit processes [2], including micromachining [3] and nanoscale manufacturing [4]. Additionally, based on such energy use studies, a number of papers have investigated and proposed energy efficiency improvements in the general design of machine tools [5], for conventional mechanical cutting machines [6], for laser cutting machines, in particular for sheet metal applications [7] and for manufacturing support systems such as robotics [8], cooling [9], power factor correction [10] and pneumatics [11]. Alternative approaches to the time consuming power measurements required by such energy investigations have also been proposed [12]. Non-conventional micro-machining processes such as abrasive blasting and laser cutting have received less attention. Moreover the focus of research to date has been on changes to future design, while the energy optimisation of machinery already in production is not often considered. This is important given the extended life of many production machines currently in operation.

This paper provides an overview of the energy use in an inkjet manufacturing facility, with a specific focus on Diode Pumped Solid State (DPSS) lasers and high pressure abrasive jet machines for microdrilling applications. Since the abrasive jet and laser drill units are alternative stages in the process chain, an energy usage comparison of both technologies is presented. A number of energy efficiency measures are proposed for the laser drill machine and some of the difficulties in achieving energy savings in an industrial environment are also discussed. A particular emphasis is placed on the role or risk as a barrier to improvement.

2 CASE STUDY: INKJET MANUFACTURING

The case study is based on a large multinational manufacturer of inkjet printer cartridges. The factory produces large volumes of printer cartridges, and in addition to dedicated production buildings the campus also includes other business units such as sales, marketing and also contract manufacturers/component suppliers. The order of magnitude of annual energy consumption is in the double figure GWh scale, with electricity accounting for 67% of usage. The price for electricity is approximately twice the price of natural gas in Ireland at present. The 2011 CO_2 intensity for electricity and gas in Ireland was 0.49 kg-CO_2/kWh, including the additional overhead for processing/transport of fuel, and 0.2 kg-CO_2/kWh (NCV) respectively. Electrical energy is therefore the major driver of energy use, costs and CO_2 emissions on site. An energy management system (Powerlogic, Schneider Electric) and extensive power metering allows for electricity consumption tracking and identification of significant energy consumers.

2.1 Factory energy use

There are a large number of technologies and processes used in the production of a final printer cartridge product. The main process stages located in the factory include 1/ Print Head Manufacture (PHM) and 2/ Final Assembly (FA). Figure 1 shows the breakdown of energy supply and final consumption for the factory. Note, in figure 1 'other electric energy' refers to the electricity usage of other business units located on the campus. Air compressors and production

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

machines are the largest electrical energy consumers, accounting for 23% and 21% of usage respectively. Within the production category, print head manufacturing equipment consumes approximately 65% of overall production electricity use. The energy usage due to space heating, ventilation and air conditioning (HVAC) is also large, considering the combined consumption of the air handling units, boilers and chillers accounts for nearly 50% of total site energy usage.

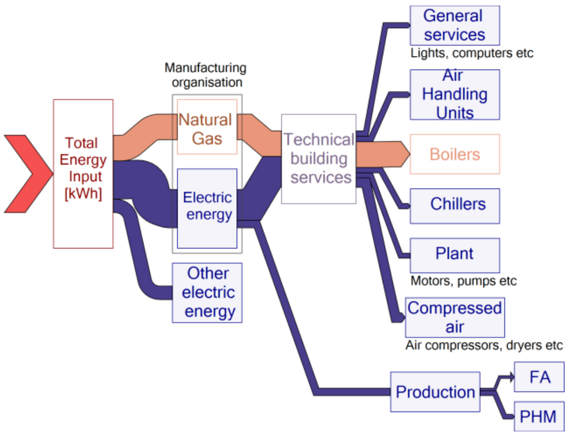


Figure 1: Energy breakdown in inkjet manufacturing facility.

3 PRODUCTION MACHINE ENERGY USE

In order to cut slots of micron spatial scale in a wafer, as part of the print head manufacturing process, two alternative micromachining methods are utilized: abrasive blasting and laser drilling. Laser drilling accounts for a considerable proportion (approx. 20%) of the electrical energy consumed in PHM, and the abrasive jet machines require an additional 110kW dedicated compressor to deliver compressed air at higher pressure than general factory requirements. Therefore both processes are considered significant energy users and were investigated as part of the site energy efficiency program. Note that while the general purpose of both the laser and abrasive jet machines is the same, typically different products, i.e. different slot dimensions, are produced on each.

In terms of the system boundaries for the study, only the electrical power and compressed air demand of the machine tools were measured. The difference in energy usage in post-cut treatment processes and TBS support equipment (e.g. vacuum pumps, dust collectors), required by the sandblast and laser drill machines, was therefore not considered. The energy usage of lighting and ventilation was also outside the scope of the investigation. Unit process level measurements were taken at supply points to the machines e.g. compressed air dropdown pipe or electrical panel. A mobile power meter (HT Italia VEGA78) and two air flowmeters (CS instruments VA420, VP instruments VPF) were used for the measurements. A one second integration period was used for the power meter and the flowmeters were sampled at a rate of 1Hz. The specific power required by the air compressors supplying the machine tool was estimated to be 6 kW/Nm3/min at 7 bar(g) and 7 kW/Nm3/min for 10 bar(g), assuming an overall adiabatic efficiency of 80%.

3.1 Laser drill electrical power demand

A number of laser drill machine tools are shown in figure 2. The main components of the tool include two solid state, diode pumped, Q switched laser heads and associated equipment: controller, galvanometer etc (figure 3). The average output power of a laser in operation is 30W at 120 kHz with material removal via ablation. An air-cooled vapor compression chiller provides cooling for both laser heads and galvanometers. Laser cooling is a critical function as semiconductor devices such as diodes perform better at lower operating temperatures resulting in higher electrical to optical efficiency and extended device lifetime [13]. An XY linear translation stage in each chamber is used for precise positioning of the wafer, and a single robot loads the wafers into each laser head chamber. Other components include: PC's, PLC, cameras, actuators, sensors, cooling fans etc. The nominal energy requirements of the machine are 22A per phase at 400VAC (50 Hz 3 Phase) and 500NL/min at 6 bar(g).

Figure 2: Laser drill machines.

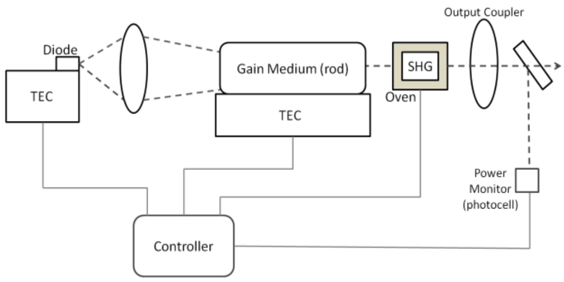


Figure 3: DPSS Laser system subcomponents without Q-switch.

The breakdown of subsystem nominal electrical power requirements for the laser machine tool is shown in figure 4 and is based on data from vendor datasheets. It is clear from figure 4 that the majority (65%) of electrical power demand is due to the laser systems and chiller. A sample power measurement of the machine in operation is shown in figure 5 and demonstrates that the actual proportion of electrical energy usage due to the chiller and lasers will be higher than 65%. This is due to the fact that the robot, whilst nominally having the third largest power rating, only operates for brief loading/unloading periods between wafer processing, and is otherwise in standby mode. A similar energy breakdown was found for the laser cutting of sheet metal [7]. Within each laser head, the Electricity Consuming Units (ECU's) are the Thermo-Electric Coolers (TEC), crystal ovens for Second Harmonic Generation (SHG), diode array and controller (figure 3). The ECU's in the chiller include compressor, pump and fan. The total measured electrical power demand during production and idle mode was 4.9 kW and 3.3 kW respectively. It should be noted that the machine tool is only fully shutdown on rare occasions. The overall wall plug efficiency, ratio of optical output power to total electrical input, of the laser head is estimated to be approximately 3%. This figure is based on the total power demand of the laser system, including TEC's, controller etc, but does not consider the additional energy usage of the chiller. Wall-plug efficiency is often described in terms of the ratio of optical output power to the electrical power delivered to the diodes only [14]. Using this definition, efficiencies of 25% to 28% for solid state lasers, e.g. Nd:YAG, are reported in the literature [14].

The main air consuming units (ACU's) include a venturi vacuum generator for wafer handling, air knifes to prevent water or debris settling on galvonometer lens surfaces, air nozzles to assist the cutting process, and pneumatic cylinders for clamping and actuation. There was a small difference in compressed air demand on the laser tool for the water and air assisted portion of slot ablation process. The equivalent electrical power, due to average measured compressed air demand, was 1.8 kW in production mode and 1.38 kW when idle. Air leakage was found to account for approximately 10% of overall compressed air demand. The power required to supply compressed air is approximately 27% of overall power demand by the laser tool.

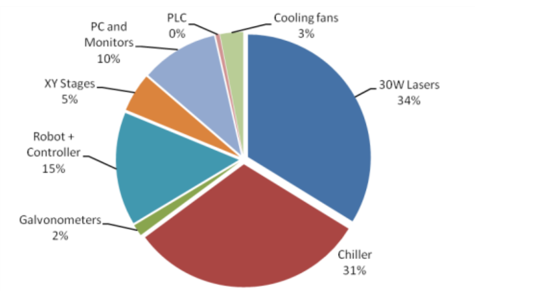


Figure 4: Subsystem nominal power requirements for laser drill.

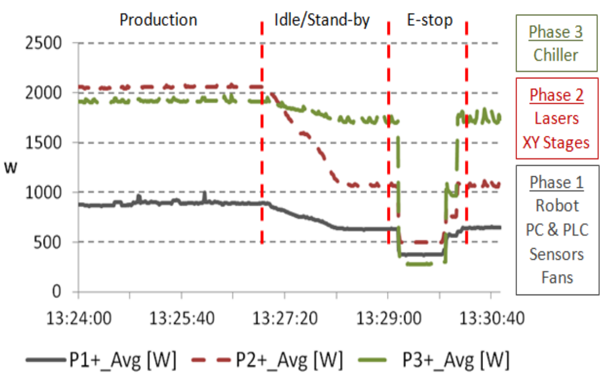


Figure 5: Sample power demand on laser drill.

3.2 Abrasive jet drill electrical power demand

In abrasive jet machining, a stream of very fine abrasive particles, such as aluminium oxide, are propelled by a pressurised gas to impinge a substrate and remove material via erosion. The main components of the sandblast machine tool (figure 6) include two high pressure nozzles in separate blast chambers, positioning tables for each chamber, a robot for loading/unloading wafers, an extraction system, vision inspect system, actuators, PC's, PLC, sensors etc. The nominal electrical energy requirements of the machine are 8A at 230 VAC (50 Hz Single Phase). Two compressed air lines are required to supply air at a lower pressure of 6 bar(g) and a higher pressure of 9 bar(g). Note, the higher air pressure is required from a process point of view, to achieve a defined material removal rate.

In addition to the energy penalty associated with using higher air pressure to increase production throughput, the air quality also affects both energy usage and process output. The compressed air used in the abrasive jet machining process is in direct contact with sensitive electronic components and must therefore be dried, in order to ensure there is no condensation of water vapour on the product with subsequent reduction in production yield. The additional energy usage for dehumidifying the air will depend on the type of air dryer in operation i.e. refrigerant or adsorption. The high pressure compressed air system in the inkjet factory includes heatless desiccant dryers with a relatively low dewpoint of -70°C. The compressed air requirements to purge heatless desiccant dryers accounts for a considerable portion of overall compressed air demand, typically in the range of 15% to 25% of rated capacity [15]. In order to incorporate the additional air demand into the estimate of required air compression power, the measured compressed air flow to the machine was multiplied by a factor of 1.25. Note this purge flow factor will depend on the type of desiccant dryer, inlet air temperature and specified dewpoint. The pressure drop across the air system is also increased with desiccant dryers.

A sample measurement of the high and low pressure compressed air demand is shown in figure 7, with one blast chamber in operation. The equivalent electrical power required to supply the compressed air at both higher and lower pressure levels was estimated to be 5.9 kW in production mode and 2.2 kW in idle. The electrical power demand of the sandblast tool was measured to be 1kW on average during production mode and 0.5 kW when idle. The electric power required to supply compressed air is approximately 85% of overall power demand of the abrasive jet machine.

Figure 6: Abrasive jet machines.

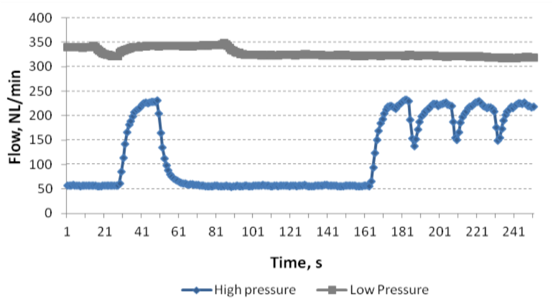


Figure 7: Sample compressed air demand on abrasive jet tool.

3.3 Comparison of energy use for laser and abrasive jet micromachining processes

A comparison of the aggregate power demand, including electrical and compressed air, and specific energy for both machines tools is shown in table 1. Interestingly, the estimated power demand of the abrasive jet machine in production mode is 0.2kW more than that of the laser, but the power draw in idle mode, is considerably (2 kW) less. The power requirements of the sandblast machine in production mode could be reduced through the use of a heat regenerated desiccant dryer. The smaller idle energy requirements of the sandblast unit are due in part, to the ability of pneumatic components to provide a continuous force without needing a continuous feed of energy. This idle energy usage could be reduced further with leak detection and fixing. However considering processing time only, the specific energy required per wafer is less for laser machining than abrasive machining, due to the smaller production mode power demand and shorter cycle time of the laser machine tool. The wafer processing time will vary based on the number of slots required per wafer and slot dimensions, which depend on the product type in production. Therefore for consistency, in table 1 the specific energy per wafer is based on the same product type. It is important to highlight that there is an ongoing migration from the older sandblast to laser drill technology and the process time for the laser drill in table 1 is therefore based on preliminary test data. The main benefits of laser drilling include enhanced production yield and improved product quality, in the form of smoother edges after cutting. The higher quality surface finish ultimately allows for improved functional performance of the inkjet cartridge during the use phase. Therefore the reduction of idle time and idle power demand are keys issues for improved energy efficiency. Note, this analysis does not consider the additional energy related overheads for the laser drills to be located in a cleanroom environment, with associated HVAC requirements, or the dust collection units necessary for abrasive jet machine operation.

	Laser Drill	Sandblast
Production power, kW	6.7	6.9
Idle power, kW	4.7	2.7
Process time, mins/wafer	35*	40
Specific energy, MJ/wafer	14. 1	16.6

Table 1: Power and energy use comparison for micromachining MT's.

4 ENERGY EFFICIENCY IMPROVEMENTS

The laser drill machine tools were the focus of the energy efficiency analysis. The financial viability/return on investment of EEM's can be determined by net present value or internal rate of return methods but the simple payback method is still prevalent in industry.

4.1 Energy saving options - Laser Drill

The energy efficiency improvements discussed for the laser drill are shown in table 2 and are broken into two categories: 1/ No or low cost idle mode optimisation measures and 2/ Design changes, involving the replacement of subsystems or components with newer or more efficient alternative technology. In particular the use of power factor correction [10], kinetic energy recovery methods [6, 8] and alternative coolers using scroll compressor technology [9] look promising in the development of new machine tools. However, given the large capital investment required for laser machine tool components (robot, laser system etc), combined with relatively low energy use and costs, makes the economic case for design changes, such as the replacement of subcomponents, difficult. Additionally, the stringent short term focussed payback requirements of multinational manufacturers also hampers the implementation of energy efficiency measures. Therefore the best potential for efficiency improvements on operational production machinery involves the reduction of idle mode power demand. In the case of the laser drill tool, shutdown of the main energy consumers, laser systems and chiller, over longer time periods, such as weekends, offered significant energy savings. Based on discussions with technical personnel, the shutdown procedure was modified such that problematic older PC's were left on, to avoid software issues on restart. The use of software for the controlled shutdown of the robot for shorter standstill times (e.g. 10mins) [8] also offered considerable savings, given the long idle time of the unit during production mode. Potential savings of around 300,000 kWh per annum were identified for the laser drill production zone with little or no investment costs.

Idle optimisation
Soft shutdown of tool over extended idle periods (>8 h)
PC and monitor shutdown over extended idle periods
Controlled shutdown of robot for idle periods (>10 mins)
Alternative chiller control when idle
Turn off Galvonometer air knives when idle
General optimisation
Regenerative brakes for XY stage and/or robot
Dynamic power factor correction
VSD for chiller pump and/or fans
New IE3 electric motor for chiller
Complete replacement of chiller
Eliminate second PC or replace PC's with newer models
Replace single acting pneumatic cylinders with muscle actuators

Table 2: EEM's for Laser Drill.

5 RISK AND ENERGY EFFICIENCY IN PRODUCTION

In addition to economic and technical efficiency considerations, the risk to product quality and machine availability also require thorough investigation to successfully implement energy saving projects. Risk or perceived risk by operations staff to even relatively simple measures, for example the shutdown of equipment, can prevent the ultimate uptake of EEM's. An early assessment of risk and mitigation plan based on input from technical staff and original equipment manufacturers is therefore essential for the success of energy efficiency projects in production. Some of specific concerns associated with the shutdown of the laser drill over extended periods include:

- Algae growth in the chiller water supply. Risk of increased machine downtime for maintenance.
- Dew condensation in the laser head cavity. Since the laser crystal is hygroscopic, any exposure to moisture can result in crystal degradation and potential failure. There is a subsequent risk of machine downtime and/or product quality issues.
- DPSS lasers are sensitive to temperature, operation outside tight limits can lead to fluctuations in output power, and impaired cutting performance. Risk of reduced yield at start of production run.
- Potential for thermal drift of optical components in laser system leading to slot misalignment and reduced tool yield at start-up.

There is therefore the possibility of significant future expense, due to the extra personnel and time required for machine correction in addition to component replacement costs, should any of the described risks occur. The risk of such occurrences is generally reduced when laser machine tools are situated in temperature and humidity controlled cleanroom environments, as condensation and large temperature fluctuation are unlikely. However, the potential losses are clearly a serious barrier to the implementation of EEM's on operational production machinery.

5.1 Initial risk assessment

Failure Mode and Effect Analysis (FMEA) is qualitative risk evaluation technique that is widely used to identify potential failure modes based on expert experience and knowledge. This approach has been recently applied to a biomedical production machine, in order to address concerns regarding product quality and machine reliability, in relation to planned energy efficiency improvements [16]. The draft ISO14955 standard prescribes that machine tools are to be described in terms of their generalised functions to facilitate analysis and problem solving in relation to energy efficiency [17]. In keeping with this approach, the matrix presented in table 3 allows for the risk of fault, due to implementation of an EEM, to be assigned by the machine tool functions and components. This initial risk assessment can then be followed by comprehensive evaluation of the specific concerns, using Failure Mode and Effect Analysis (FMEA) for example, to assess the severity of EEM induced failure, probability of failure occurrence and likelihood of failure detection.

Generalised MT functions	Component/Sub-System	EEM1	EEM2	...	EEMn
Machine operation (Process, motion, control)	Laser Head	Y/N	Y/N		Y/N
	Galvonometer	Y/N	Y/N		Y/N
	XY stage	Y/N	Y/N		Y/N
	PLC	Y/N	Y/N		Y/N
	PC & monitors	Y/N	Y/N		Y/N
	Vision system, sensors, transformer, UPS etc	Y/N	Y/N		Y/N
Process condition/cooling	Air assist system Water assist system	Y/N Y/N	Y/N Y/N		Y/N Y/N
Workpiece handling	Robot Wafer chuck	Y/N Y/N	Y/N Y/N		Y/N Y/N
Tool handling	Lens purge	Y/N	Y/N		Y/N
Waste handling	Vacuum supply (TBS) Vacuum pump (optional)	Y/N Y/N	Y/N Y/N		Y/N Y/N
Machine cooling/heating	Chiller Fans	Y/N Y/N	Y/N Y/N		Y/N Y/N

Table 3: Example EEM fault risk matrix for Laser Drill.

6 DISCUSSION ON RISK IN ENERGY RELATED INTERNATIONAL STANDARDS

The existing international standard for energy management systems [18] or the draft standard for environmental evaluation of machine tools [17] focus on energy measurement, monitoring and top level management commitments to improve energy efficiency. While such measures are an essential starting point, the risk or perceived risk to industrial key performance indicators such as machine availability and product yield is a critical barrier to the final implementation of energy efficiency measures. At present, a systematic approach for risk assessment and mitigation of energy efficiency measures is not explicitly addressed in the international standards.

Additionally, while a risk centric approaches to energy efficiency has been successfully applied in industry [16], the method is time consuming for two reasons primarily: 1. The necessity of consulting the original machine developers and 2. In overcoming strong organisational resistance to any changes to the status quo, in particular if production personnel are not subject to energy metrics. Therefore, it would be useful for the machine builders to either design for controlled shutdown over extended periods e.g. non 24/7 production, or provide a risk assessment for the end-user to do same.

7 CONCLUSIONS

The energy use in terms of electricity and compressed air, for two micromachining processes, laser and abrasive jet drilling, has been investigated in this paper, and it has been shown that moving product from sandblast to laser drill results in a small decrease in the specific energy for machining a wafer. However, some of the savings in specific energy will be offset by the higher idle electrical energy consumption of the laser tool and the change in overall factory energy use will therefore depend on the production schedule of the machine tool. A number of energy saving opportunities were identified for the laser drills, with a focus on idle mode optimisation for reasons of economic efficiency. The important role of risk in the implementation of energy efficiency measures has also been highlighted and in this context, some specific risk factors involved in the shutdown of laser based production systems as an example, were discussed. Given that machine uptime and product quality are typically prioritised ahead of energy savings, thorough risk assessment of machine or process changes is therefore an essential accompanying task to any industrial energy saving project. Finally it is has been proposed that risk assessment and mitigation should be considered for integration into future international standards regarding manufacturing energy efficiency and energy management.

Future potential work includes a total cost of ownership study of the abrasive jet and laser machine tools, including maintenance, consumables and facility support systems, to provide a more comprehensive insight into overall operational costs. Other environmental impacts, such as the use of sand or other abrasive material, could also be considered. Additionally, from an industrial point of view, holistic methods that prioritise energy efficiency measures for production tools based an assessment of technical/economic efficiency and risk, are required.

8 ACKNOWLEDGEMENTS

The work reported in this paper has been carried out with funding from the Irish Research Council and Hewlett Packard Manufacturing through the Enterprise Partnership Scheme.

9 REFERENCES

[1] Müller, E. and Löffler, T. Improving energy efficiency in manufacturing plants–case studies and guidelines. 16th CIRP International Conference on Life Cycle Engineering. 2009.

[2] Gutowski, T., Dahmus, J., and Thiriez, A. Electrical energy requirements for manufacturing processes. 13th CIRP International Conference on Life Cycle Engineering 2006. Leuven, Belgium.

[3] Diaz, N., Redelsheimer, E., and Dornfeld, D. Energy consumption characterization and reduction strategies for milling machine tool use. 18th CIRP International Conference on Life Cycle Engineering. 2011. Braunschweig, Germany.

[4] Zhang, T.W., Boyd, S., Vijayaraghavan, A., and Dornfeld, D., Energy Use in Nanoscale Manufacturing, IEEE International Symposium on Electronics and Environment 2006, San Francisco, CA.

[5] Zein, A., Li, W., Herrmann, C., and Kara, S., Energy efficiency measures for the design and operation of machine tools: an axiomatic approach, 18th CIRP International Conference on Life Cycle Engineering, 2011, Braunschweig, Germany.

[6] Diaz, N., Helu, M., Tonissen, S., Dornfeld, D., and Schlosser, R. Strategies for Minimum Energy Operation for Precision Machining. MTTRF Annual Meeting. 2009.

[7] Devoldere, T., Dewulf, W., Deprez, W., and Duflou, J.R., Energy Related Life Cycle Impact and Cost Reduction Opportunities in Machine Design: The Laser Cutting Case, 15th CIRP International Conference on Life Cycle Engineering 2008.

[8] Meike, D. and Ribickis, L. Energy efficient use of robotics in the automobile industry. 15th International Conference on Advanced Robotics (ICAR). 2011. IEEE.

[9] Brecher, C., Baumler, S., Jasper, D., and Triebs, J. Energy Efficient Cooling Systems for Machine Tools. 19th CIRP Conference on Life Cycle Engineering. 2012. University of California at Berkeley, USA.

[10] Neugebauer, R., Kolesnikov, A., Richter, M., and Paetzold, J. Improvement of the power factor correction in machine tools. 14th International Conference on Power Electronics and Motion Control. 2010.

[11] Harris, P., O'Donnell, G.E., and Whelan, T. Energy efficiency in pneumatic production systems: state of the art and future directions. 19th CIRP Conference on Life Cycle Engineering. 2012. University of California, Berkeley, California, USA.

[12] Steinhilper, R., Freiberger, S., Kubler, F., and Bohner, J. Development of a Procedure for Energy Efficiency Evaluation and Improvement of Production Machinery. 19th CIRP Conference on Life Cycle Engineering. 2012. University of California at Berkeley, USA.

[13] Thermal Considerations in Design of Water-Cooled DPSS Laser Systems, Coherent, www.coherent.com.

[14] Wall-plug Efficiency, RP Photonics Consulting GmbH, www.rp-photonics.com.

[15] Barber, A., Pneumatic Handbook. 8th ed. 1997, Oxford, UK: Elsevier Advanced Technology.

[16] Aughney, N. and O'Donnell, G.E. Lean Energy: A methodology to Characterise and Optimise Energy and Resource Consumption within Manufacturing Process Chains. 10th Global Conference on Sustainable Manufacturing 2012. Istanbul, Turkey.

[17] ISO14955-1 Machine tools - Environmental evaluaton of Machine Tools (draft), Part 1: Design methodology for energy-efficient machine tools 2012, International Organisation for Standardisation, Switzerland.

[18] ISO 50001 Energy Management Systems, Requirements with Guidance for Use 2011, International Organisation for Standardisation, Switzerland.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

11.3 Energy saving by using a redundantly actuated parallel mechanism

G. Lee [1], JI. Jeong [2,*], S. Kim[1], D. Lee [3] and J. Kim [1]
[1] School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea
[2] School of Mechanical Engineering, Kookmin University, Seoul, Korea
[3] School of Mechanical Engineering, Soongsil University, Seoul, Korea

Abstract
In this work, energy saving by using a redundantly actuated parallel mechanism is presented. The redundantly actuated parallel mechanisms have more actuators than the degrees of freedom of the mechanisms. We show that the excessive actuators can be used to save operating energy of the mechanism by distributing the operating torques against the gravitational force. The energy saving is verified by experiments for a 2-DOF parallel mechanism with three actuators, which is operated against the gravity. The results show that the redundant actuation scheme can save about 25% of average energy in various pathways with respect to the non-redundant analogue.
Keywords:
Parallel kinematics, Energy efficiency, Redundant actuation

1 INTRODUCTION

Parallel mechanisms consist of several serial chains that connect a base to a moving platform. Because of their structure, parallel mechanisms are known to be capable of very fast and accurate motions and to carry heavier payloads than their serial analogues is capable. These advantages however come at the expense of a reduced workspace from singularity configurations, difficulty in mechanical design procedure, and more complex control algorithms. A singularity is a configuration in which the degrees of freedom of a parallel mechanism change instantaneously, which must be eliminated for enlarging workspace of the mechanism. One method to eliminate the singular configuration is to add one or more actuators into one or more of the passive joints [1-3].

Redundantly actuated parallel mechanism usually increases cost of the mechanism system because of additional actuators. Thus, the more energy efficient control algorithm is needed to compensate the manufacturing or purchasing cost of the redundant parallel mechanisms [4-6]. Approach to the motion generation methodology can be categorized into two concepts: minimum torque and minimum consumed energy. The minimum torque approach is focused on lowering the maximum torque of the actuators to be installed. This approach has an advantage in reducing the initial cost in building a machine. However the positioning platforms such as router and spot welding robot need to reduce the operational expenditure rather than initial cost. In this paper, the minimum energy strategy is adopted to reduce actuating energy by adding an excessive actuator in a parallel manipulator.

There are some relative researches about trajectory planning of redundant or non-redundant serial robots [7-11]. However there seems to be not so many previous works on energy efficiency for redundant parallel mechanism. In this paper, the energy saving feature by using redundantly actuated parallel mechanism is presented. By adding additional actuators, the parallel mechanism can consume lower energy compared to non-redundant systems do. Experimental verification has also been done with a 2-DOF redundantly actuated parallel mechanism machine.

This paper is organized as follow. The kinematic and dynamic analysis is presented for a 2-DOF redundant actuated parallel mechanism in Section 2. In Section 3, simulation results for energy saving by redundant actuation is presented. The experimental verification with seven test path is depicted in Section 4. Finally, some concluding remarks follow in Section 5.

2 METHODS

2.1 Kinematic analysis

A planar 2-DOF parallel manipulator is used for verifying the energy saving feature by redundant actuation. Figure 1 shows the schematic diagram of the 2-DOF planar manipulator, which consists of a triangular plate platform, a base frame, and three serial l_{1i}, l_{2i}, l_3 chains. The serial chains l_{1i} and l_{2i} consist of two links (l_{11}, l_{12}) and (l_{21}, l_{22}), respectively, but the chain l_3 consists of only one link.

In the case of non-redundant control, two active actuators are enough to realize the 2-DOF motion. However, three to eight actuators can be attached and the mechanism will be operated with the over-actuated control.

The equations of motion for the suggested mechanism can be derived from the constraint equation, which represents geometrical constraint of the mechanism during the operation. In case of the 2-DOF mechanism, the constraint equation $g(\cdot)$ can be written as equation (1).

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

$$g(\cdot)=0:\begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix}=\begin{bmatrix} \|\mathbf{p}_1-\mathbf{p}_2\|^2-D_1^2 \\ \|\mathbf{p}_2-\mathbf{p}_3\|^2-D_2^2 \\ \|\mathbf{p}_3-\mathbf{p}_1\|^2-D_3^2 \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

The equation means the distance among the point $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$ from the base coordinate should be equal to the side of the triangular platform. $\mathbf{p}_1$, $\mathbf{p}_2$, and $\mathbf{p}_3$ are the triangular position of the platform. D_i is the length of a side of the platform. Then, a Jacobian is defined as the linear relationship between the time derivatives of the related variables. The detailed derivation of equations is given in previous works [12].

Constraint Jacobian is the velocity relationship between the independent joint vector q_u and the dependent joint vector q_v. This relationship can be obtained by the time derivative of the geometric constraint equations $g(\cdot)$. By differentiating the constraint equation, the relationship between the velocity of the independent and actuating joint angles can be derived such as equation (2).

$$\dot{q}_r=\begin{bmatrix} \dot{q}_u \\ \dot{q}_v \end{bmatrix}=\begin{bmatrix} I_{2\times 2} \\ \Phi \end{bmatrix}\dot{q}_u=\Gamma\dot{q}_u \quad (2)$$

where q_u and q_r are the independent joint vector and actuating joint vector respectively. Φ is a Jacobian mapping independent joints to dependent joints. Here Γ is a Jacobian mapping independent joints to actuating joints. These Jacobians will be used to perform dynamic analysis. The Jacobian matrix of above equations considered can be used to obtain the elements of dynamic analysis as mass, Coriolis force, and a generalized force of system.

2.2 Dynamics analysis

The dynamics of a robot manipulator describes how the robot moves in response to these actuator forces. The dynamics analysis is generally classified into forward and inverse dynamics analysis in robotics literature. The forward dynamics analysis is to find the resulting motion of the end-effector as a function of time by given control inputs, which are generally actuator torques and forces. In contrast, the inverse dynamics analysis is performed to find the control inputs required to produce desired end-effector motion. It can be analyzed from the given joint values and time derivatives by solving the inverse kinematics for the desired end-effector motions.

The dynamics analysis of the redundantly actuated parallel mechanism is performed based on the results of the non-redundant case. To obtain the general motion equation of the redundantly actuated parallel mechanism, the actuating and passive joints values have to be expressed as the function of the generalized coordinates. But in case of redundantly actuated parallel mechanism, the number of active joints is larger than that of independent joints. Thus the principle for torque distribution is needed, and torques on all actuating joints with redundantly actuated joints could be calculated with minimal torque distribution [4]. From minimal torque distribution algorithm, torques of the redundant system τ_r can be expressed with Jacobian Γ which maps velocity of

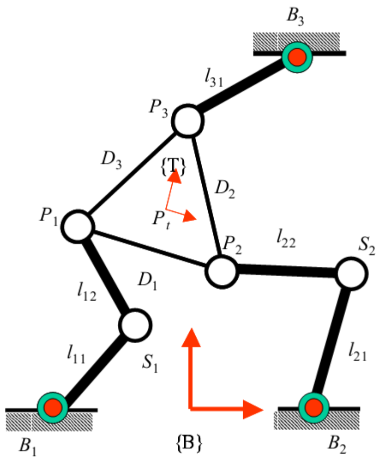


Figure 1: Schematic diagram of a 2-DOF planar manipulator

the independent joints to velocity of the redundantly actuated joints.

$$\tau_u=\Gamma^T\tau_r \quad (3)$$

where τ_u is torque of the actuators in non-redundant case. If there is no internal forces in the system the torques of redundant system can be expressed as equation (4).

$$\tau_r=\Gamma(\Gamma^T\Gamma)^{-1}\tau_u \quad (4)$$

Then dynamic equation of redundantly actuated parallel manipulator can be established finally.

$$M\ddot{q}_u+C\dot{q}_u+N=\Gamma^T\tau_r \quad (5)$$

With the torques of redundantly actuation discussed in this Section, the trajectory planning based on dynamic modelling can be carried out.

2.3 Energy analysis

In the manipulator system, electric motors are usually exploited to actuate the joints. The absolute value of the power signal that is calculated by multiplying torques and the angular velocity of the actuating joints can be used for the energy calculation such as equation (6).

$$E_r=\int\left(\sum_{i=1}^{l}\left|\tau_{ri}\dot{q}_{ri}\right|\right)dt \quad (6)$$

where τ_{ri} is the torque and the $\dot{q}_{ri}$ is angular velocity of the i-th actuating joint, respectively.

In the case of non-redundant actuation for the 2-DOF mechanism in this work, the energy can be written as equation (7).

$$E_u=\int\left(\left|\tau_{u1}\dot{q}_{u1}\right|+\left|\tau_{u2}\dot{q}_{u2}\right|\right)dt \quad (7)$$

where τ_{u1} and τ_{u2} is the torques of the independent actuators in non-redundant case. For the redundantly actuated case, the energy equation can be obtained as equation (8).

$$E_r = \int \left(|\tau_{r1}\dot{q}_{r1}| + |\tau_{r2}\dot{q}_{r2}| + |\tau_{r3}\dot{q}_{r3}| \right) dt \tag{8}$$

where τ_{r1} , τ_{r2} and τ_{r3} is the torques of the actuating actuators in the redundant case. These torque vectors should satisfy the relationship suggested in equation (2) and (5) if the both actuation method can produce same motion of the manipulator.

The work done by the actuators can also be defined as follows:

$$W_r = \int \left(\sum_{i=1}^{l} \tau_{ri}\dot{q}_{ri} \right) dt \tag{9}$$

3 SIMULATION

Simulations are carried out to compare the consumed energy of redundant actuation and non-redundant actuation. In case of the non-redundant actuation, the two actuators are assumed to be installed in the base position of B_1 and B_2 in Figure 1. The additional actuator is assumed to be installed on B_3 in the case of redundant actuation.

The 2-DOF redundantly parallel manipulator is designed to apply the external forces to the mechanism system. With vertical configuration of the mechanism, simulations with the proposed mechanism are performed to obtain the consumed energy caused by external forces, which is gravity in this case.

Seven linear pathways are proposed as Figure 2 so as to verify the energy saving by redundant actuation. The start points and end points of test paths are selected so that all the point during each pathway should be included in the workspace of the system and so that avoid the singularity region. The dark region in Figure 2 represents the actuator singularity of non-redundant system, yet there is no actuator singularity in the workspace of the redundant system. The specific discussion about singularity of the parallel mechanism can be found in previous works [2], [12].

In Table 1, simulation results of the energy consumption for the two systems are compared. From the results of the simulation, the redundant system is observed to require smaller energy than that of non-redundant system in all the pathways. As an example, work done by actuators and consumed energy in both cases of redundant and non-redundant actuation during the pathway are depicted in Figure 3. The end-effector starts from point (-150mm, 400mm) and arrives to the point (-30mm, 100mm) in the end of the pathway. In the figure, the red solid line represents the power by non-redundant actuation during the pathway, where only two actuators at the B_1 and B_2 in Figure 1 are used for the manipulation. The green dashed line represents the power by redundant actuation with respect to time, which used three actuators at B_1, B_2 and B_3. From the simulation results, the consumed energy of both cases can be calculated as the area below each graph, that is, the integration of the power with respect to the operation time.

The simulation results show that the work by actuators in both cases is almost equal to each other, which presents the same result in Section 2. In contrast, the consumed energy

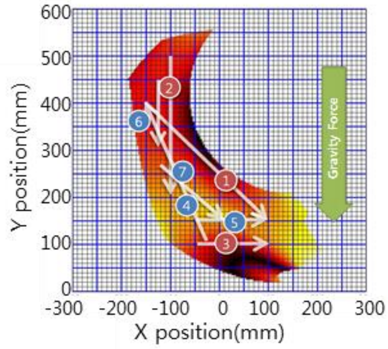
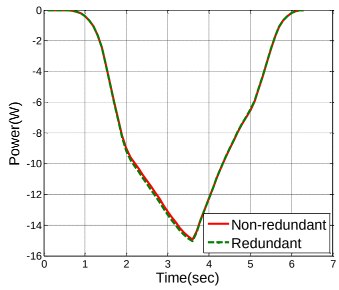
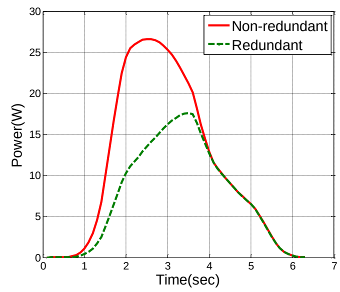


Figure 2: Test paths of 2-DOF redundant parallel manipulator



(a) Work done by actuators



(b) Consumed energy by actuators

Figure 3: Work done by actuators and consumed energy of 2-DOF redundant parallel manipulator in case 6: from position (-150,400) to (-30,100).

Table 1: Comparison of energy consumed between redundant system and non-redundant system (simulation)

Path No.	Redundant system (Joule)	Non-redundant system (Joule)	Rate of change (%)
1	4371.80	7193.69	-39.23
2	4873.42	5966.91	-18.33
3	1001.04	1466.09	-31.72
4	2139.48	3272.69	-34.63
5	1093.05	1099.03	-0.54
6	4597.90	6459.35	-28.82
7	4556.44	5495.20	-17.08

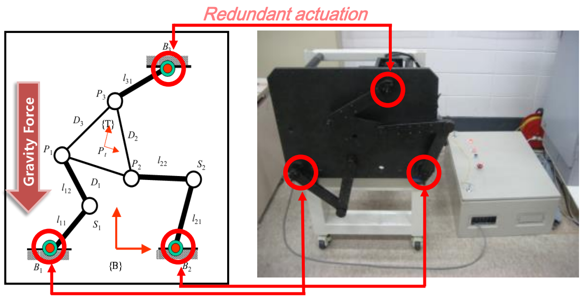


Figure 4: Experimental setup for
a 2-DOF redundantly actuated parallel manipulator.

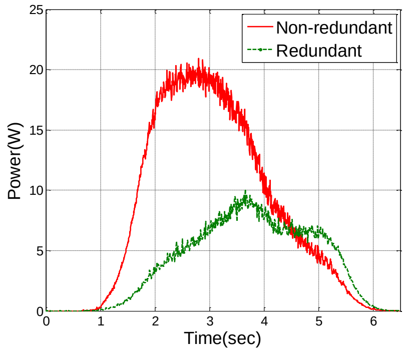


Figure 5: Experimental result of the consumed energy of 2-DOF redundant parallel manipulator in case 6: from position (-150,400) to (-30,100).

Table 2: Comparison of energy consumed between redundant system and non-redundant system (measurement)

Path No.	Redundant system (Joule)	Non-redundant system (Joule)	Rate of change (%)
1	3840.05	6136.85	-37.43
2	3228.14	4368.60	-26.11
3	1726.20	2015.90	-14.37
4	1098.85	2457.47	-55.29
5	1873.03	1577.04	18.77
6	2781.16	5196.45	-46.48
7	5984.24	5903.63	1.37

by the redundant actuation is smaller than that by non-redundant actuation.

The energy saving by using the redundant system compared non-redundant system can't be found in the horizontal planar mechanism system without gravity. In the case, the consumed energy of redundant system and non-redundant system are same. This result is caused by geometry work in the motion, which means that negative work caused by actuators [7]. The negative work is generated when the direction of the torque and angular velocity are different. In the situation the actuator is operated as a brake system against the angular motion of the joint related. Thus, the simulation results in Figure 3 means geometry work of redundantly actuated system is reduced compared to non-redundantly actuated system because of torque distribution among the actuators installed including the additional actuators.

The difference of reduction ratio among the test paths is influenced by configuration of mechanism during the trajectory. The consumed energy efficiency of redundant system can be increased in comparison to non-redundantly actuated system, if configuration of redundant actuator is designed for desired point-to-point path of system.

4 EXPERIMENTAL RESULTS

To verify the simulation result of optimization, experiments are carried out with the 2-DOF redundantly actuated parallel mechanism machine as Figure 4. The experiments were executed with this machine. The torques and velocity of actuators were measured from the Clipper PMAC2 controller of DeltaTau. Then the torques and angular velocity were multiplied with each other and integrated with operation time to generate the consumed energy of the actuators. The detailed experimental results are depicted in Table 2. The measured consumed energy in the case of 6th pathway is suggested in Figure 5.

The experimental results presents that the consumed energy by the redundant actuation is saved about 23% in average for the test cases. However, consumed energies of redundant actuation in the 5th and 7th cases are higher than the non-redundant case.

The difference between simulation result and experimental result seems to be caused by friction of joint mechanisms. In case of the go-up paths as path number 3, 5, and 7 the friction usually induces excessive actuation torque. Therefore the friction makes measured energy greater than estimated consumed energy.

On the other hands, the friction in go-down paths as path number 2, 4, and 6 causes the decrease of torques of actuators. That is why the measured data with these paths is smaller than estimated data. To overcome these errors, the friction calibration model should be considered in the dynamic modelling as a future work.

5 CONCLUSION

This paper presents the energy saving feature by using redundantly actuated parallel mechanism against gravitational force. Experimental results are suggested with the vertical 2-DOF redundant parallel machine.

The optimization based on dynamic modelling with minimal torque distribution is used to obtain the minimum consumed energy path. Also this paper shows that consumed energy of redundantly actuated parallel mechanism is less than non-redundantly actuated system with continuous external force such as gravity force. The reason of this consumed energy reduction is that torque distribution with additional actuators of redundantly actuated parallel mechanism can reduce the geometry work of electrical actuators of system. This result will be another advantage of redundantly actuated parallel mechanism in an energy perspective as well as a workspace perspective which is considered previous researches.

The vertical 2-DOF redundant parallel machine is used to verify the algorithm. Both the simulated and experimental results show that the redundant parallel manipulator has advantage in reducing consumed energy compared to non-redundant parallel manipulator.

6 ACKNOWLEDGMENTS

This work was supported by research program of Kookmin University in Korea, the IGPT Project (N0000005) of the Ministry of Knowledge Economy in Korea and National Research Foundation (NRF) grant funded by the Korea government (MEST) (No. 2012-0000348).

7 REFERENCES

[1] Kim J, Hwang JC, Kim JS, Iurascu C, Park FC, Cho YM (2002) Eclipse II: A new parallel mechanism enabling continuous 360-degree spinning plus three-axis translational motions. IEEE Transaction on Robotics and Automation 18/3: 367-373.

[2] Jeon D, Kim K, Jeong JI, Kim J (2010), A calibration method of redundantly actuated parallel mechanism machines based on projection technique. Annals of CIRP 59/1: 413-416.

[3] In W, Lee S, Jeong JI, Kim J (2008) Design of a planar-type high speed parallel mechanism positioning platform with the capability of 180 degree orientation. Annals of CIRP 57/1: 421-424.

[4] Park D, Lee S, Kim S, Kwak Y (2003) Torque distribution using a weighted pseudoinverse in a redundantly actuated mechanism. Advanced Robotics 17, 807-820.

[5] Park FC, Kim J (1999) Singularity analysis of closed kinematic chain. ASME Journal of Mechanical Design 121/1: 32-38.

[6] Kim J, Cho YM, Park FC, Lee JM (2003) Design of a parallel mechanism platform for simulating six degrees-of-freedom general motion including continuous 360-degree spin. Annals of CIRP 52/1: 347-350.

[7] Chou L, Song SM (1992) Geometric work of manipulators and path planning based on minimum energy consumption. ASME Journal of Mechanical Design 114: 414-421.

[8] Diken H (1994) Energy efficient sinusoidal path planning of robot manipulators. Mechanism and Machine Theory 29/6: 785-792.

[9] Westkamper E et al. (1998) Task-oriented programming of large redundant robot motion. Robotics and Computer-Integrated Manufacturing 14: 363-375.

[10] Jouaneh MK, Wang Z, Dornfeld DA (1990) Trajectory planning for coordinated motion of a robot and a positioning table: part 1 – path specification. IEEE Transactions on Robotics and Automation 6/6: 735-745.

[11] Halevi Y, Carpanzano E, Montalbano G, Koren Y (2011) Minimum energy control of redundant actuation machine tools. Annals of CIRP 60/1: 433-436.

[12] Jeong JI, Kang D, Cho YM, Kim J (2004) Kinematic calibration for redundantly actuated parallel mechanism. ASME Journal of Mechanical Design 126/2: 307-318.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

11.4 Extending the boundaries of energy management for assessing manufacturing business strategies

E. Woolley [1], L. Sheldrick [1], J. Arinez [2], S. Rahimifard [1]
[1] Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University, UK
[2] Manufacturing Systems Research Lab, General Motors R&D Center, Michigan, USA

Abstract
Manufacturers are responsible for about one third of global energy demand, and thus have a responsibility for reducing their reliance on rapidly depleting non-renewable energy sources. Consequently, a plethora of research has arisen to develop novel ways of improving energy efficiency in factories by focusing on changes to energy intensive production processes and other energy using systems that support manufacturing activities. However, the ultimate goal of manufacturing companies is to maximise profit by refining their business strategy, highlighting the importance of assessing the impact of different business strategies on energy demand. Therefore, one of the key research challenges is to assign anticipated energy demand to various decisions within a business. This paper presents a hierarchical approach to attribute the potential energy demand of manufacturing activities to alternative business decisions, thus informing selection of the most energy efficient business strategies.

Keywords:
Energy Management, Business Strategy, Manufacturing, Life Cycle Analysis, Sustainable Manufacturing

1 INTRODUCTION

It has been well documented and is widely agreed that the future global community will not have access to the same level of energy-rich fossil fuels that we enjoy today. This limitation may be of some environmental benefit as it will naturally limit our tendency to generate CO_2, however, it also creates a significant challenge for communities, governments, industries and end users who currently rely on inexpensive energy to sustain their activities. Broadly speaking, there are two options available for reducing our reliance on fossil fuels: significant and prolonged investment in renewable energy resources, or systematic and continuous efforts for reduction in primary energy demand. In terms of cost-effectiveness, the latter option appears to be the most attainable in the short to medium term. However, in order to meet the growing energy challenges ahead, future initiatives are likely to comprise a combination of both approaches.

Radical improvements in energy efficiency will be of particular importance to the manufacturing industry which currently represents approximately one third of global energy demand. In addition, many manufacturing companies are already struggling to remain profitable in poor economic climates, and will need to become more resilient to increases in the cost of energy and/or shortages in future energy availability. Even with these drivers it is recognised that a business is unlikely to change its profit model based on energy use alone, however, energy is likely to become an increasingly important consideration and will form a key decision factor for company managers in the not-too-distant future.

Historically, successful manufacturing businesses have been those that produce and sell more than their competitors, leading to widespread disregard for resource consumption and pollution levels. However, business strategies are beginning to change as companies seek new ways to remain competitive, and implement new approaches to win market-share whilst reducing operating costs. These emerging business models carry different energy foot-prints when compared to historical models. For instance, in the case of pay-per-use washing machines, the business owner, and not the end user, is responsible for the cost of the energy used during the use phase. Similarly, for cars sold in Europe and Japan, the manufacturer is responsible for processing and recycling of the vehicles at their end-of-life. Therefore, this additional energy demand (and its associated cost) needs to be accounted for during business planning.

This highlights the need for an approach to establish the energy demand implications of potential business decisions, enabling the manufacturing industry to intelligently identify and select the most energy efficient business strategies. A three stage method is proposed in this paper which attributes potential energy demand to business strategies, thus identifying radical energy efficiency opportunities. The broad applicability of this energy assessment for business strategies is then demonstrated through the consideration of an example product.

2 A BRIEF REVIEW OF ENVIRONMENTAL BUSINESS PLANNING AND ENERGY MANAGEMENT STRATEGIES

Over the last few decades, there has been a proliferation of research which has delivered a range of methodologies and tools for improving energy efficiency in manufacturing companies. These approaches have mainly focussed on technology or reactive end-of-pipe improvements to manufacturing activities. Although such approaches are suitable for incrementally improving energy efficiency in make-sell business models, more radical reductions in energy use can be achieved through innovative business models that meet consumer needs without the emphasis on selling large volumes of products.

As such, the appropriateness of existing business models are being challenged [1, 2], and many studies are suggesting a dramatic evolution such as those introducing new concepts of cradle-to-cradle [3], localised manufacturing [4], product service systems [5], and product compatibility and upgradeability [6].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

To help companies systematically consider the inclusion of environmental factors in their business planning, a number of tools such as the 'Sustainable Business Scorecard' [7] have been developed. In relation to this, Boons *et al*. [8] have recently discussed a range of studies which explore the different ways that established companies have developed sustainable business models for their products. These studies have highlighted that current changes are predominantly driven by a reactionary approach to regulatory or social pressures and therefore deal mainly with business transition management and the adaptation of existing businesses to be retrofitted with relevant environmental considerations. It can also be seen that whilst a great deal is known about the drivers for more sustainable business models, very little is known about how to develop more sustainable businesses from the outset [8]. Existing studies do however offer useful insights into decision making and highlight a number of research gaps in both the planning of comprehensive sustainability in businesses [9] and in addressing strategic company objectives such as improving resource efficiency (e.g. energy, water or materials) to achieve specific sustainability goals [10].

Instead of approaching these objectives from the corporate level, sustainability improvements are often addressed directly at isolated levels within a manufacturing organisation. In particular, the current field of research on improving manufacturing energy efficiency is typically focused on physical energy using activities at various manufacturing levels. These levels can be described in terms of a hierarchical system similar to the 'Shop Floor Production Model' developed by the International Organisation for Standardisation (ISO) [11]. An adaptation of this model for describing energy use [12] (as shown in Figure 1), has five levels which include:

- **Turret**: energy considerations at the tool-chip interface have led to very process specific research in this area [13, 14], being largely defined by the materials used and products manufactured.
- **Machine**: includes the many energy using activities that make up a process, adding complexity. Research focusses on either the direct energy required to carry out the work, or auxiliary energy required to support manufacturing activities [15].
- **Machine cell**: energy use from the supply of material resources, transport systems, waste material processing, product maintenance, better planning and production engineering and management [16].
- **Facility:** energy use by the infrastructure and other indirect manufacturing requirements such as ventilation, lighting, heating and cooling [17].
- **Enterprise**: includes a range of activities from the supply chain of materials to the logistics of finished products [18]. At the enterprise level there is scope for efficiency improvement activities directly related to business strategy, for example Seliger *et al*. [19] made a comparison of energy required for remanufactured and make-use-dispose products.

In general, the processes developed for incorporating sustainability into business strategies are non-structured and based on the implementation of piece-meal approaches to improving certain aspects of company performance.

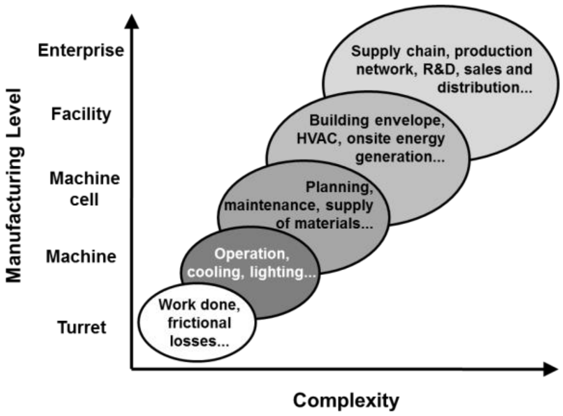


Figure 1. Energy considerations at different manufacturing levels. Adapted from [12].

Consequently, for a business manager, it is difficult to identify how decisions will impact the amount of energy required at each of these manufacturing levels, and even less so, what the full energy implications are for these decisions. This is due to a disconnect between the objectives of business strategies and the way in which current energy management systems operate. Hence, there is a need to develop a systematic process that allows a comprehensive evaluation of business strategy with respect to energy demand.

3 RESEARCH METHODOLOGY

Company planning activities can be targeted at two different strategic levels within any given organisation. The first is **corporate strategy** which applies to planning across the whole enterprise. The second is **business strategy** which applies more specifically to defining the choice of product, service, and market [20]. At the corporate strategy level, significant changes are rare and transitions typically occur on a more evolutionary basis due to heavy restrictions from inflexible factors such as company location or a mature supplier network. However, at the business strategy level, decisions can be more readily linked to energy consuming activities by defining the types of products to be manufactured, the nature of services to be provided, and other supporting activities required at the enterprise level. Therefore, this research is focussed on assessing business strategies to identify future energy demand for a manufacturing company.

In order to effectively assess potential energy demand at the business strategy level, it will be important to assign activities to different decisions using a systematic method. Therefore, instead of attributing energy use to the infrastructure of an enterprise (as can be done through the use of the ISO model), it is more appropriate to attribute energy to manufacturing activities required to deliver and support a particular product, thus allowing a comparison between different strategies that meet similar customer needs.

In this context, an extended version of the '3P perspective' proposed by Seow and Rahimifard [21] can be used to assign components of energy use to either the **product**, the **processes** or the **plant**. In order to account for the entire range of the activities which can determine the energy footprint of a business strategy (in particular within medium to large manufacturing companies), an additional perspective needs to be included in this approach. This new perspective consists of activities at the '**corporation**' level, which accounts for all energy using activities outside the company's plants (e.g. logistics, sales and marketing offices). Together, the combination of these four holistic categories can be deemed the '**3PC perspective**'.

A number of new and emerging business models such as product service systems (PSS) require a company to have further interaction with a product beyond the point of sale, for example through maintenance or take-back activities. It is therefore important to consider the energy requirements of these additional life cycle stages within any energy assessment. In order to account for this, the 3PC perspective should be applied for each phase of the product life cycle as illustrated in Figure 2. Clearly, one of the key considerations in this new approach is to avoid the 'double accounting' of energy demand between the different energy perspectives. This approach can then be used to identify energy use hotspots within a business strategy, or used to compare different strategies that fulfil the same consumer need in the same market. This will ultimately enable manufacturers to reduce the overall energy input required for their business activities by enabling the selection of the most appropriate strategies, and identification of any inefficient areas.

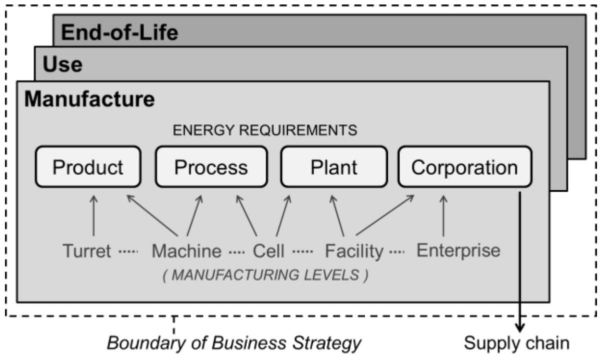


Figure 2. Defining the required energy considerations for business strategy energy modelling.

4 ATTRIBUTING ENERGY DEMAND TO BUSINESS STRATEGY

As with any business strategy, there should always be a focus on meeting the need or demand of the customer to ensure long-term success. Nowhere is this more true than in manufacturing where the most successful business strategies are those that remain focused on the product. In these cases, the processes, plant and corporate structure are then defined by the requirements of the product and consumer need. The method for establishing the potential energy demand of a business strategy should therefore assume the same approach, starting with the requirements for the product, and then adopting a bottom-up approach (from processes to plant and corporation levels) to identify the total energy requirements of the company. However, in order to be able to determine the appropriate energy consuming activities (i.e. those for which a company is economically accountable), it is necessary to first establish the boundaries for a company's energy considerations. In this context, a three stage approach is presented below to model and reduce the energy demand for a business strategy.

Stage 1 – Setting the Energy Demand Boundaries: These should include everything that a manufacturer is responsible for, or has direct control over during the entire product(s) life cycle(s). However, these should also be limited to exclude factors such as the extended supply chain which are outside the manufacturer's direct control and for which they are not responsible for the cost of energy use. The scope of energy using activities included will vary depending on the business strategy under consideration (e.g. reverse logistics required for remanufacturing) but should certainly include significant factors under the responsibility of the manufacturer (e.g. environmental control for spray booths).

In this context, there are two key dimensions in which a manufacturer should use to define the boundaries for their energy demand: a) the various product life cycle stages, and b) the entire manufacturing infrastructure (as defined by 3PC prospective). The relevant stages of the product life cycle that need to be considered are determined by the choice of business strategy. For example, in a make-sell approach, neither the 'use' nor 'end-of-life' stages will incur an energy demand from the manufacturer, whereas the implementation of a PSS may require energy expenditure during the use as well as end-of-life stages of the product, as illustrated in Figure 3. In terms of infrastructure, the energy using activities under consideration will depend upon the way a product is manufactured and provided to the customer. Using both the life cycle and manufacturing infrastructure dimensions to define the boundaries of energy consideration enables manufacturers to identify the complete range of key attributes which should be included in their energy assessment.

Stage 2 – Attributing Energy to Business Activities: This stage involves quantifying each energy requirement that the manufacturer is economically accountable for, as defined in Stage 1. Within any manufacturing business, there will be a vast number of energy using activities, and so a structured approach is required whereby each activity is clearly defined and assigned an energy value (e.g. in kJ or BTU). By using the proposed 3PC perspective, energy can then be attributed to a range of specific activities that are influenced by the business strategy. It should be noted that each of these four perspectives represent a number of activities across various product life cycle stages that should be included in the energy model, as outlined below:

Product – Transforming a quantity of material, or materials, into a product requires a minimum theoretical amount of energy as defined by physical laws [15]. The fundamental energy required to manufacture a product, E_{Prod}, can thus be deduced either by calculation from known principles, or by retrieving LCI data from one of the commercially available LCA databases.

Processes – Beyond the theoretical energy required to manufacture a product, the processes within a manufacturing facility require additional energy in order to power auxiliary units (e.g. coolant systems, tooling and fixturing systems, computer control). An amount of energy is also typically lost through inefficiencies within the process (e.g. heat generated through machining processes). All of these various factors must be taken into consideration when compiling the total process energy demand. The energy required to run the manufacturing processes, E_{Proc}, for a single product can be obtained or calculated from equipment data sheets or from empirical monitoring of existing processes.

Plant – The energy consuming activities not directly associated with production processes can be attributed to a manufacturing plant. These typically include systems that maintain a production environment and includes HVAC, lighting, internal transport, offices, security, etc. The energy requirements at plant level, E_{Plan}, can be deduced from its dimensions and environmental data, as well as the requirements for computing and other business support systems, or from measuring (metering) its current energy use. The total energy requirement for a plant over a set period needs to be amortised for each product produced at that plant.

Corporation – Extending beyond the walls of the plant, this level considers potential energy demand for transportation of materials and products, product warehousing, external sales and marketing offices, etc. The energy requirement for these enterprise level activities, E_{Corp}, can be estimated from readily available transport energy data, known distribution nodes, and through the use of a similar approach to the 'plant' perspective for non-manufacturing buildings.

Each of the above energy perspectives will likely include a number of energy using activities (e.g. one factory may have tens or hundreds of processes). In this respect, the energy level notation E_{Proc} should be replaced with the terms $E_{Proc,1}$, $E_{Proc,2}, \ldots E_{Proc,n}$ for *n* production processes. This also applies to E_{Prod}, E_{Plan}, and E_{Corp}, and therefore, for the manufacturing stage of the life cycle, the predicted energy demand is:

$$E_{Manuf} = \sum_{i=1}^{n} (E_{\mathrm{Prod},i} + E_{\mathrm{Proc},i} + E_{Plan,i} + E_{Corp,i}). \tag{1}$$

Similarly, the total energy attributable to a business strategy, E_{BS}, can be defined as:

$$E_{BS} = \sum_{Manuf}^{EoL} \left[\sum_{i=1}^{n} (E_{\mathrm{Prod},i} + E_{\mathrm{Proc},i} + E_{Plan,i} + E_{Corp,i}) \right], \tag{2}$$

where, the product life cycle stages consist of manufacturing (Manuf), use (Use) and end-of-life (EoL).

Figure 3 illustrates the total energy demand for three business strategies, namely make-sell, producer responsibility (in which manufacturer is responsible for take back and recycling of their product), and product service system. Clearly, in the cases where business strategies require the manufacturer to have an interaction with the product after the manufacturing stage (e.g. PSS), then the 'use' and 'end-of-life' stages of that product's life cycle becomes a significant consideration due to the additional energy demand during these stages.

It should also be noted that this assessment of energy demand has to be considered with respect to an expected 'functional unit' within an application which could be defined in terms of time, number of uses, unit cost, etc.

Stage 3 – Reducing the Energy Demand for a Business Strategy: Once the potential energy demand for a business strategy has been determined it is possible to then either analyse the data to highlight the energy hotspots and thus focus efforts for improvement in energy efficiency or to compare the strategy with other potential approaches to revenue generation. In terms of identifying and addressing energy hotspots, there are a number of methods of analysis as described in Rahimifard *et al.* [15]. By following the three stage approach presented above, manufacturers are able to plan and include all of the relevant energy requirements in their business models and thus use a single procedure to make suitable comparisons between different business strategies, or different energy using activities across a product's life cycle.

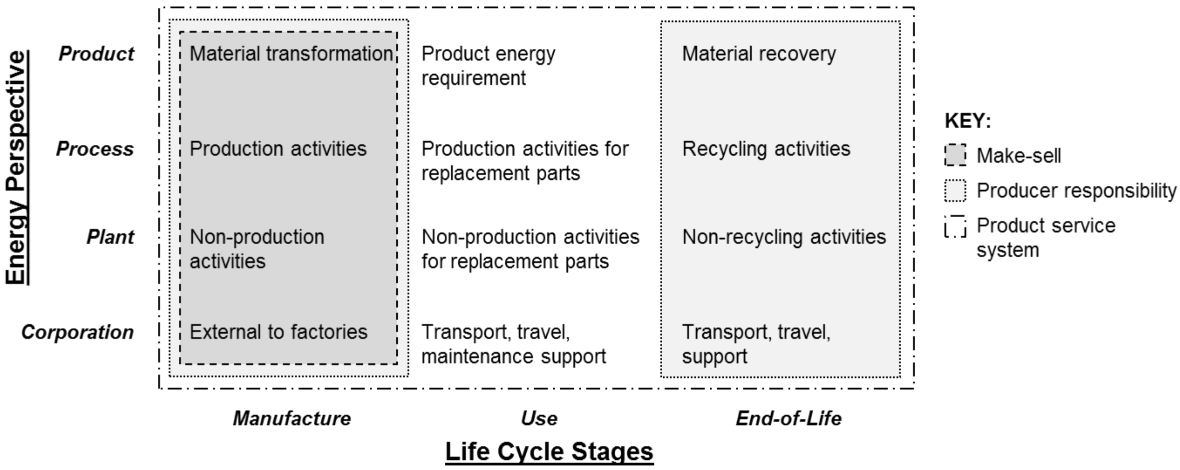


Figure 3. Mapping of boundaries for different business strategies.

5 COMPARING ENERGY DEMAND FOR A MAKE-SELL AND PSS BUSINESS STRATEGIES

The following example compares different business strategies for the manufacturing and provision of steel roofing using energy data from a study conducted by Kara and Manmek [18]. In this example two business strategies are compared in terms of their potential energy demand per product year, one supplying steel roofing panels via a traditional make-sell business strategy, the other supplying identical roof panels via a PSS business strategy. In the latter instance, the manufacturer is responsible for the panels' maintenance throughout their lifetime plus their end-of-life recovery. Therefore, in terms of energy consideration boundaries, the make-sell business strategy is concerned only with the manufacturing stage of the product life cycle, but the PSS business strategy needs also to consider the maintenance of the panels during 'use' phase plus energy required to recover the steel at its end-of-life. In this case study, since it is the same product supplied to the user based on different business strategies, the energy requirements for the manufacture of the panels has been assumed to be identical. It should be noted that in other applications, a manufacturer may choose to improve the quality of their product (to extend its use life) under PSS business strategy, and thus the manufacturing energy demand may significantly vary.

The energy data summarised in Table 1 are calculated for both business strategies based on information provided by Kara and Manmek [18] and from calculated theoretical requirements for known production processes and transportation methods. It has also been assumed that, if the manufacturer instigates the recovery of the material, they can off-set any energy benefit against their manufacturing energy requirements. In addition, the lifetime of the steel roofing for the make-sell and PSS business strategies has been assumed to be 15 and 25 years respectively; the PSS roofing having, on average, an extended lifetime due to a regular maintenance schedule.

Energy Contributor	Make-Sell	PSS
<u>Manufacture</u>		
E_{Prod}	33 MJ/m^2 *	33 MJ/m^2 *
$\Sigma(E_{Proc} + E_{Plan})$	145 MJ/m^2 #	145 MJ/m^2 #
ΣE_{Corp}	2 MJ/m^2 #	4 MJ/m^2 &
<u>Use (maintenance)</u>	N/A	
ΣE_{Corp}		2 MJ/m^2 yr &
<u>EoL</u>		
E_{Prod}		-48 MJ/m^2 #
ΣE_{Corp}		4 MJ/m^2 &
L_P	15 yr	25 yr
E_{BS}	12 MJ/m^2 yr	7.5 MJ/m^2 yr

** = data calculated from physical material properties*

 # = data taken or inferred from [18],

& = data simulated from company/customer location

Table 1. Energy requirements considered through product life cycle for comparison between make-sell and PSS business strategies for steel roofing.

Despite the additional energy requirements from the PSS business strategy during the 'use' and 'end-of-life' stages over that of the make-sell approach, that the energy requirement per square-metre per year of the roofing is less, as shown in Table 1. This is because the energy demand for the manufacturing stage of the product (mostly due to $\Sigma(E_{Proc} + E_{Plan})$) represents the largest energy outlay for the company, and so preserving this investment in energy (through the use of additional energy during use and EoL) by adopting a PSS business strategy becomes a worthwhile task. However, in other cases where the product in question did not require as much energy to manufacture, it might be less beneficial to use further energy for maintenance during its lifetime.

It should also be noted that in this example, the energy expenditure on maintenance (50MJ/m^2 over 25 years) is almost entirely recuperated by the energy off-set from reusing/reprocessing of the material at the end of its life. As a result, an extension to the product life by a further 67% yields a reduction in energy per functional unit of 38%, demonstrating a more energy efficient approach to meeting the customer need through the application of a different business strategy.

From the data in Table 1 it is possible to further investigate the specific energy contributions from various aspects of the business model in order to identify and address any energy demand hotspots. An analysis of the predicted energy demand per year for the above PSS business strategy is shown in Figure 4. In this example, the contribution to E_{BS} from $E_{Proc} + E_{Plan}$ is a dominating factor and requires further investigation in order to identify specific energy contributing activities. This analysis however is based on high level data, and a more detailed analysis would be required in practice (e.g. to include the energy requirement of individual manufacturing processes) in order to establish the true potential for energy demand reduction in the PSS strategy.

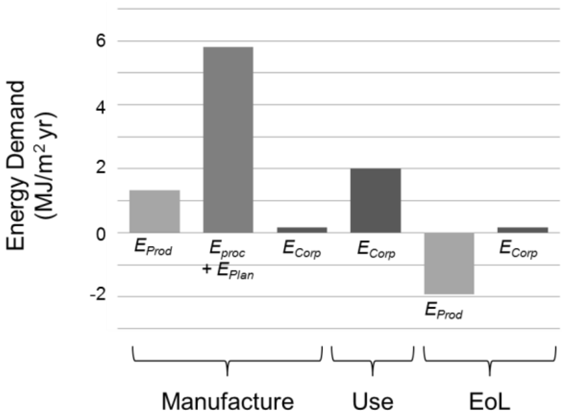


Figure 4. Comparison of the life cycle energy demand components, averaged per year, for the example PSS of steel roofing panels.

6 CONCLUSIONS

Despite the well-recognised need to better manage the way the manufacturing industry uses energy, demand continues to increase. The potential future problems faced by industry in terms of energy cost and availability could be catastrophic causing significant global shrinkage of manufacturing output. Correspondingly, much research has been published detailing tools and methods for addressing energy management, monitoring, and efficiency within the physical infrastructure of manufacturing enterprises. However, the research reported in this paper has argued that the energy demand of a manufacturing company is significantly influenced by its business strategies

A three stage approach to attributing and minimising the predicted energy demand for business models has been presented and its application has been demonstrated using an example product based on make-sell and PSS business strategies.

Ultimately, the management of energy at the business strategy level needs to integrate with existing business considerations (e.g. profit, resilience, established supply chains) to inform better decisions. At present, manufacturers' primary consideration in choosing a business strategy comes down to profit, and it is unlikely that manufacturing activities will be fully optimised solely for their energy efficiency. In this respect, assigning a cost to energy within the proposed energy modelling approach in this paper could allow manufacturers to assess not only the current financial implications of different energy requirements, but also factor into their decision making processes the likely rises and fluctuations in the cost of energy. It is envisaged that this approach for assessing energy demand for various business strategies is likely to become increasingly important in the next few decades.

REFERENCES

[1] Comes, S. and Berniker, L., 2008. Business model innovation. *From Strategy to Execution***,** 65-86.

[2] Lee, K. & Casalegno, F., 2010. An Explorative Study for Business Models for Sustainability. *PACIS 2010 Proceedings***,** 47.

[3] Braungart, M., Mcdonough, W. & Bollinger, A., 2007. Cradle-to-cradle design: creating healthy emissions-a strategy for eco-effective product and system design. *Journal of Cleaner Production,* **15,** 1337-1348.

[4] Kumar, K., 2004. *From post-industrial to post-modern society: New theories of the contemporary world.* 2nd ed. Wiley-Blackwell

[5] Tukker, A., 2004. Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet. *Business strategy and the environment*, **13**, (4), 246-260.

[6] Li, Y., Xue, D. and Peihua, G., 2008. Design for Product Adaptability, *Concurrent Engineering*, **16**, 221-232.

[7] Figge, F., & Hahn, T., 2002. The Sustainability Balanced Scorecard – linking sustainability management to business strategy. *Business strategy and the environment*, **11**, (5), 269-284.

[8] Boons, F., Montalvo, C., Quist, J., Wagner, M., 2013. Sustainable innovation, business models and economic performance: an overview, *Journal of Cleaner Production*, **45**, 1-8.

[9] Boons, F., and Lüdeke-Freund, F., 2013. Business models for sustainable innovation: state-of-the-art and a step towards research agenda, *Journal of Cleaner Production*, **45**, 9-19.

[10] Lambooy, T., 2011. Corporate Social Responsibility: sustainable water use, *Journal of Cleaner Production*, **19**, (8) 852-866.

[11] ISO, 1990. ISO TR 10314-1: Industrial Automation – Shop Floor Production, International Standards Organisation: Switzerland.

[12] Vijayaraghavan, A., and Dornfeld, D., 2010. Automated energy monitoring of machine tools, *CIRP Annals - Manufacturing Technology*, **59**, (1) 21-24.

[13] Kalpakjian, S. and Schmid, S. R., 2008. *Manufacutring Processes for Engineering Materials,* Prentice Hall, Singapore.

[14] Draganescu, F., Gheorghe, M. and Doicin, C. V., 2003. Models of machine tool efficiency and specific consumed energy, *Journal of Materials Processing Technology,* **141,** (1) 9-15.

[15] Rahimifard, S., Seow, Y. and Childs, T. (2010) Minimising Embodied Product Energy to support energy efficient manufacturing, CIRP Annals - Manufacturing Technology, 59, (1) 25-28.

[16] He, Y., Liu, F., Cao, H., 2005. Process Planning Support System for Green Manufacturing and its application. *Computer Integrated Manufacturing Systems* **11,** (7) 975-980.

[17] Boyd, G., Dutrow, E., and Tunnessen, W., 2008. The evolution of the ENERGY STAR® energy performance indicator for benchmarking industrial plant manufacturing energy use. *Journal of Cleaner Production* **16,** 709-715

[18] Kara, S., and Manmek, S., 2010. Impact of Manufacturing Supply Chains on the Embodied Energy of Products. Proceedings of the 43rd International Conference on Manufacturing Systems.

[19] Seliger G., Kernbaum, S., and Zettl, M., 2006. Remanufacturing approaches contributing to sustainable engineering., *Gestao & Producao,* **13,** 367-384.

[20] Andrews, K. R., 1997, The concept of corporate strategy, in Resources Firms and Strategies, Foss, N. J. (ed) Oxford University Press, Oxford, UK.

[21] Seow, Y. and Rahimifard, S. (2011) Improving Product Design Based on Energy Considerations, In *Glocalized Solutions for Sustainability in Manufacturing* (Eds, Hesselbach, J. r. and Herrmann, C.) Springer Berlin Heidelberg, pp. 154-159.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

11.5 Energy equivalent of compressed air consumption in a machine tool environment

S. Züst [1], A. Gontarz [2], K. Wegener [2]
[1] inspire AG Zurich, Switzerland
[2] Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology, Switzerland

Abstract
Compressed air has many applications in machine tools. Compared to the potential energy stored in the fluid tank its production requires a large amount of energy. In addition to the potential energy, heat loss does occur as by-products. Dependent on the amount of heat loss, energy consuming cooling is required. For life-cycle investigations of machine tools, the gray energy and environmental impacts of compressed air consumptions have to be known. This work presents a theoretical approach to quantify the energy equivalent of compressed air and its by-products. A model based approach is set up to describe the required physical relationships for the compressor and its peripheral components. Measurements obtained from a shop floor compressed air supply have been used to validate the results of the theoretical approach. Concluding from the analysis, a general approach for the theoretical energy equivalent calculation, including the compressor and treatment of heat loss, is possible.

Keywords:
Compressed air equivalent, machine tool modeling, energy monitoring

1 INTRODUCTION

Compressed air is a frequently used energy carrier in machine tools. Some examples of possible applications are pneumatic components, tool handling or protection of machine components by sealing air. Compressed air is a resource consumed by the machine and therefore related to the energy and resource efficiency. Energy efficient machine tool design is an emerging topic. In this context, the ISO standard 14’955-1 is under development and has reached the level of a drafted international standard (DIS) [1]. For an energy analysis according to the new standard, all energies supplied to the machine tool must be known. Further, the energy content of all the resources must be expressed in a common unit, in order to allow a synthetisation of the different energy flows to the total consumption but also for comparison of different energy carriers.

Compared to other energy carriers, compressed air is a cost intensive medium [2, 3]. The cost is mostly caused by the electricity needed for the compressor supplying compressed air [4], amplified by inefficiencies and thermal effects making up to 93% of the electric input power [5]. Machine tools generate heat loss during operation; therefore excess heat is an issue of great importance. Whereas the supply of compressed air causes excess heat in a remote part of the factory, the use of compressed air, i. e. the decompression in a machine tool, represents a heat sink, causing a direct impact on its thermal conditions.

Power measurements on machine tools have shown a substantial share of energy for the thermal conditioning of the manufacturing process and of the machine tool itself, including compressed air consumption [6]. For the evaluation of energy efficiency of machine tools as well as for modeling for analysis and optimization purposes, quantification of energy needs on component level by selective measurements are essential. This is required by ISO/DIS 14’955 [1] and is successfully demonstrated by Gontarz et.al. [7]. In case of multiple energy supplies, i. e. electricity and compressed air, the need of a common unit for consolidation and respective conversion equivalents is obvious.

Goal of this work is the derivation and validation of an electrical energy equivalent for compressed air used by a machine tool. As the machine tool environment is a thermal sensitive area, heat sources and heat sinks must be evaluated with care. The equivalent must further be adaptable for various conditions, e.g. different pressure levels, system characteristics, operational schedules and degrees of system integration.

2 STATE OF THE ART

Electric energy equivalents for compressed air can be obtained from measurements or estimated by models. Measured energy equivalents are specific for a certain compressed air system configuration, whereas models allow a generic parametrizable approach. Gauchel [5] introduced assessment approaches for compressed air, that are in line with assessment and improvement approaches from Energy Schweiz [8]. Joseph and D’Antonio [9, 10] showed different ways for the compressed air system assessment. The authors mentioned a production effort of 0.12 to 0.27 kWh/m^3 at nominal conditions for supply pressures in the range of 7 to 8 bar. Nominal conditions are defined in DIN 1343 [11]. For the sake of simplicity only the unit ‘m^3’ is further on used, referring to cubic meter at normal conditions. Modeling of compressed air supply from the view of energy consumption was performed by Schmidt et.al. [12], D’Antonio [10], and Hütter [4]. The theoretical values for adiabatic compression are mentioned by Harris et.al [13] to be in the range of 0.08 to 0.10 kWh/m^3, dependent on the pressure. The authors as well demonstrate the quantification of heat recovery influence to the system efficiency by an exgergy based approach.

The resulting compressed air energy equivalents of Schmidt, D’Antonio, Hütter and Harris are in the range of 0.08 to 0.14 kWh/m^3. Application and use of such equivalents were successfully shown in energy monitoring and assessments

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

[14, 15]. All mentioned publications of compressed air energy equivalents consider the ratio between electrical power input to the compressor and volumetric flow per time. Energy consumptions due to secondary effects, like the treatment of heat loss, are not included. A more comprehensive energy equivalent for compressed air is required, which includes the thermal effects and distribution system pressure losses as well. Thermal effects and losses are in general very specific for each site. The new approach is thereto demanded to be adoptable to different systems, which leads to a model based equivalent. Promising modeling approaches of compressed air consuming devices by Harris et.al. [16-18] encourage a model based approach for the compressed air production electric power demand as well.

3 METHODOLOGY

In order to fulfill the above mentioned goals and requirements, a three-stage procedure is applied:

1. Identification and modeling of the relevant electric energy, pneumatic work and heat flows within a compressed air system.
2. Formulation of the theoretical energy equivalent for compressed air based on the results of the modeling.
3. Validation of the theoretical results and assumptions from the system modeling by measurements within a case study.

To derive the required energy equivalent for compressed air, a model based approach is presented. The used system model and its boundaries are shown in Figure 1. The model inputs consist of the demanded amount of compressed air V_n and inlet air conditions, represented by pressure p_{in} and temperature ϑ_{in}. The outputs of the model are the required electric energies W_{el} and thermal losses Q_{th}.

Given this dependency and the system boundary above, the energy equivalent in this approach is defined as:

$$C_{cair} = \frac{\sum_j W_{el,j} + \sum_i W_{th,i}\left(Q_{th,i}\right)}{V_n} \tag{1}$$

Including the electric components with consumptions $W_{el,j}$, and the function $W_{th,i}(Q_{th,i})$, describing the energy required to treat the i-th thermal loss $Q_{th,i}$. Objective of the following sections is to display the electric power demand and heat generation as a function of the consumed compressed air V_n at normal conditions and quantify the energy demand including thermal losses.

In order to identify the relevant energy flows – electric and thermal – a simple model is derived from the system described in Figure 2: Air enters the air system at certain conditions, is compressed by the compressor and cooled to the temperature ϑ_{out}. The compressed air is stored in a vessel until it is used by a machine tool. As shown in Figure 2, the inlet, production and consumption are locally separated, preventing heat exchange in between.

Production of the compressed air includes the compressor, the cooler and the vessel. Since the cooler is often integrated in the compressor, both components will be modeled as one. Objective of this system is the provision of the systems downstream with compressed air at pressure level p_{comp}. For this process, the following model is used: The pressure is raised adiabatically by $\delta p \ll p_{comp}$, resulting into a temperature raise. A subsequent isochoric cooling lowers the intermediate gas temperature to ϑ_{in}. Compression and cooling are repeated, until p_{comp} is reached. Using the first law of thermodynamics for a steady state system, the following energy demand for the compressor results:

$$W_{comp} = \frac{1}{\eta_{comp}}\left[V_n \cdot \rho_n \cdot R_s \cdot \vartheta_{in} \cdot \ln\left(\frac{p_{comp}}{p_{in}}\right)\right] \tag{2}$$

The term in square brackets from Equation (2) represents the fluid dynamical work required for the compression, where the first part includes the combined motor and shaft efficiency η_{comp} of the system. Gas properties are included in the specific gas constant R_s and the density ρ_n at normal conditions. Heat losses generated by the compressor due to friction and ohmic losses are described by the compressor efficiency η_{comp} as well:

$$Q_{comp} = W_{comp} \cdot \left(1 - \eta_{comp}\right) \tag{3}$$

The isochoric temperature drop of the compressed gas within the cooler requires a heat flux $\dot{Q}_{extr}$. Integrating this flux results in the total thermal energy Q_{extr}:

$$Q_{extr} = V_n \cdot \rho_n \cdot R_s \cdot \vartheta_{in} \cdot \ln\left(\frac{p_{comp}}{p_{in}}\right) \tag{4}$$

Equation (4), in comparison with the fluid dynamical work in Equation (2), reveals that all compression work is transformed into heat energy. In other words, isothermal compression does not increase the internal energy per unit of the gas, but makes it exploitable due to the pressure drop relative to the ambient conditions.

A compressor can operate in loading, during actual compression, or idle cycle, while the compressor is running, but no air is delivered. Reasons for idle cycle can be cooling functions or ready state of the system [3, 12]. During loading

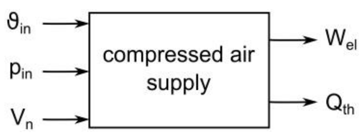


Figure 1: Boundary and interface of the discussed system.

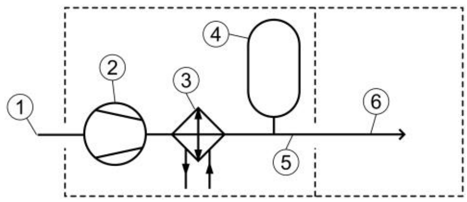


Figure 2: Simplified system model consisting of inlet (1), compressor (2), cooler (3), vessel (4), distribution system (5) and consumer (6).

cycle the system requires the electrical energy for the compressor and the cooler, while both components are generating heat loss:

$$W_{load} = W_{comp} + W_{cool} \tag{5}$$

$$Q_{load} = Q_{comp} + Q_{extr} \tag{6}$$

As mentioned by Hütter [4], the power consumptions during idle cycle are about 33% of the power demand during loading cycle. The duty cycle u represents here the ratio between the time of loading operation and the total time of operation, including idle time. With this information the total electrical energy demand and idle heat loss can be calculated according to Schmidt et. al [12] to:

$$W_{idle} = W_{cool} + W_{comp} \cdot \frac{1-u}{3u} \tag{7}$$

$$Q_{idle} = W_{comp} \cdot \frac{1-u}{3u} \tag{8}$$

The total Energy consumed and released per consumed volume V_n of compressed air by the system is now given as:

$$W_{el} = W_{load} + W_{idle} \tag{9}$$

$$Q_{th,1} = Q_{load} + Q_{idle} \tag{10}$$

respectively. Similar as for the efficiency dependent compressor power, the electric power required for the cooler is described by the coefficient of performance ε_{cool}:

$$W_{cool} = \frac{Q_{load} + Q_{idle}}{\varepsilon_{cool}} \tag{11}$$

The last element of the compressed air production system is the air vessel, an accumulator of potential energy. The compressor is operated such that the tank pressure is always between an upper and lower limit: $p_{tank} \in [p_{low}, p_{high}]$. Variation between the two pressure limits will cause a change of gas and vessel structure temperature, where the vessel structure is typically made of steel. Hence the structure is in contact with the ambient air, the vessel forms a heat sink or -source, dependent on its current temperature. In this context, it is assumed, that this heat flux can be neglected compared to compressor heat release. With this assumption and equations (9) and (10) the generative part of the system is fully described.

After the generation, compressed air enters the distribution system. In non-ideal distribution systems leakages occur. Leakage flows have to be compensated by the compressor. Given the area A_{leak} as the sum of all leak cross-sections and the total operational time t_{op}, during which the volume V_n of compressed air is consumed. Under the assumption of an isenthalpic process, the leakage loss is calculated as:

$$V_{leak} = t_{op} \cdot A_{leak} \cdot \frac{p_{comp}}{p_{in}} \cdot \sqrt{\frac{R_s \cdot \vartheta_{in}}{2}} \tag{12}$$

To model the fast expansion of the gas during the consumption, the process is separated into two parts: An isothermal expansion, followed by an isobaric expansion. The thermal energy required for the isobaric expansion is extracted from the surrounding air and can be estimated by the first law of thermodynamics as:

$$Q_{cnsp} = Q_{th,2} = c_p \cdot V_n \cdot \rho_n \cdot \vartheta_{in} \cdot \left[\left(\frac{p_{in}}{p_{comp}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \tag{13}$$

Since $p_{in}<p_{comp}$ the consumption forms a heat sink. This is obvious, since the energy required for the expansion of the gas is drawn from the surrounding.

Summarizing the results from the identification and modeling of energy and heat flows, we have the compressor and the cooler as electrical energy consumers. Further, a heat source and sink are identified: The generative part of the system generates heat loss, where the use of the compressed air draws energy from its surrounding.

In industrial applications, heat sinks and sources raise the question about additional costs and compensation. Quantifying the costs of heat loss requires knowledge about the heat management strategy. The heat sink due to decompression causes no extra costs, because excess heat is generally available in the surrounding. But the important heat source, i.d. the compressor, has a significant impact on its surrounding. Further, for simplicity reasons a linear expression of the cost is assumed:

$$K_{th}(Q) = k_{th} \cdot Q \tag{14}$$

The energy demand of the treatment is characterized by the re-use factor k_{th}. Heat dissipation can cause extra costs or can support the heating of the building. Investigating modern heating, ventilation and air-conditioning systems (HVAC) for buildings, different values for the cost factors are possible, as shown in Table 2.

Using the results of the last section, Equation (1) can be evaluated as:

$$C_{cair} = R_s \cdot \rho_n \cdot \vartheta_{in} \cdot \ln\left(\frac{p_{comp}}{p_{in}} \right) \cdot C_{sys} \cdot C_{op} \cdot C_{leak} \tag{15}$$

With

$$C_{sys} = \frac{1 + \varepsilon_{cool} \cdot (1 + k_{th})}{\eta_{comp} \cdot \varepsilon_{cool}} \tag{16}$$

$$C_{op} = \frac{2 \cdot u + 1}{3 \cdot u} \tag{17}$$

$$C_{leak} = 1 + \frac{A_{leak}}{\dot{V}_{n,avg}} \cdot \frac{p_{comp}}{p_{in}} \cdot \sqrt{\frac{R_s \cdot \vartheta_{in}}{2}} \tag{18}$$

Analyzing the structure of equation (14), the specific energy for isothermal compression scaled by system, operation and leakage specific factors can be identified. The system specific factor C_{sys} includes the performance factors of the

Table 2: Examples for possible re-use factors on different scenarios [20-22].

Scenario	re-use factor [kWh/kWh]
Heat exchange with the ambient air. The ambient air is conditioned by the HVAC.	0.3
The building is heated by electricity only. Compressor heat loss is used to heat the building.	-0.9
The building is heated by geothermal energy. Compressor heat loss is used to heat the building.	-0.25

compressor and the cooler, as well as the costs of heat sources. This costs represent the degree of system integration: Positive values indicate low system integration; e.g. the thermal energy is not used and causes additional costs. Vice versa are negative values an indicator for advanced system integration; e.g. the heat energy is used for other processes. Leakage performance is expressed by C_{leak}. This factor depends on operational settings, gas properties, leakage size, as well as average flow rate $\dot{V}_{n,avg}$ over the whole time of operation.

Examples for numerical evaluations of the compressed air equivalent are shown in Table 1, where different efficiencies, pressure levels and degrees of system integration are compared. Resulting equivalent values are within the range of 0.08 to 0.90 kWh/m^3. For high efficient systems, the estimated equivalents between 0.08 and 0.18 kWh/m^3.

4 VALIDATION

Within the previous section, a method for the calculation of the energy equivalent of compressed air in a machine tool environment has been shown. The following points need to be validated comparing computed results to measurements of real systems:

- Consistency between the measured electric power demand per volume compressed air and the calculated ratio
- Insignificancy of the heat flux over the air vessel surface

Using a measurement system according to [7] installed on a test system, the required data is collected and used for the validation.

4.1 Measurement set-up

The test system consists of a state of the art screw compressor of a European manufacturer built in 2012; with a rated motor power of 15 kW and a throughput of 2.11 m^3/min. Excess compressor heat is extracted by a fan and emitted to the ambient air. Connected to the compressor is an air vessel with a volume of 250 l. Forced by the compressor control, the vessel pressure is always between 10 and 11 bar over ambient pressure. Instead of a machine tool, an orifice is used to simulate a consumer. This orifice leads to a constant flow rate of 3.75 l/s. Due to this configuration, the compressor operates at an average duty cycle of 20% during a constant consumption. This configuration represents a rather small installation for compressed air generation.

The measured variables are the power consumption of the compressor, the volumetric flow thought the orifice, as well as the temperatures of the ambient, the vessel surface and the

Table 1: Examples of estimated compressed air electric energy equivalents for different systems, pressure levels and system integration (low efficient: u=20%, ε=2, η=30%; high efficient: u=60%, ε=4, η=80% [19]). The units of the listed equivalents are kWh/m^3 at normal conditions.

	No secondary thermal treatment	Air-Air heat exchange	Connection to HVAC, moderate climate	Connection to HVAC, cold climate
Description	Only electrical power has to be taken into account, since no secondary treatments of heat sinks and sources are required.	Heat loss is exhausted to the ambient air, which is conditioned by the HVAC of the building.	The compressor is connected to the HVAC system of the building. During six months per year the excess heat is used for heating.	The compressor is connected to the HVAC system of the building. The excess heat is used to heat the building.
6 bar				
low efficient	0.55	0.65	0.50	0.45
high efficient	0.11	0.13	0.10	0.08
8 bar				
low efficient	0.63	0.75	0.58	0.53
high efficient	0.12	0.15	0.11	0.10
10 bar				
low efficient	0.70	0.84	0.64	0.58
high efficient	0.14	0.17	0.12	0.11
12 bar				
low efficient	0.75	0.90	0.69	0.63
high efficient	0.15	0.18	0.13	0.12

exhaust air of the compressor cooler. Expected relative errors are in the range of ±4.5% for power measurements and ±3.5 % for air flow capturing. For the temperature measurement a multi-probe system from *Hygrosense* with an absolute error of ±0.3 K [23] is installed. The measurement is performed over a sufficient amount of load cycles. Resulting are the time series of the electrical power demand of the compressor, volumetric flow through the orifice and the temperatures of the ambient air, exhaust air of the cooler and the vessel surface. A cut-out of this data is shown in Figure 3.

4.2 Measurement analysis

Based on the measurement results, the energy per volume compressed air at nominal conditions can be calculated:

$$\overline{C}_{cair} = \int_{t_1}^{t_2} \overline{P}\, dt \bigg/ \int_{t_1}^{t_2} \dot{\overline{V}}\, dt \approx 0.55\,\text{kWh/m}^3 \quad (19)$$

In order to compare the measured value to the calculated value, the method described in Section 3 is applied for the present case. Based on the technical fact sheet of the compressor, a compressor efficiency of 40 % and cooler efficiency ratio of 2 can be calculated. Using the required conditions of DIN 1343 and the ideal gas properties of air all parameters for the calculation are known [10, 11, 24, 25]. With these parameters and equations (1), (15) and $k_{th}=0$ – since no heat recovery takes place, and the impact to the HVAC is not measurable – an estimated compressed air equivalent results:

$$C_{cair} \approx 0.57\,\text{kWh/m}^3 \quad (20)$$

Comparing the results of Equations (20) and (19), a relative error of 4% in the energy equivalent calculation can be identified.

During the measurement, also the temperatures of the vessel surface, as well as the temperature of the ambient air have been measured. From this measurement, a maximum temperature difference of 1 K is identified. For the vessel a surface of 4.5 m^2 can be estimated from its geometry. Under the assumption of free convection [24] with a convection constant of 5 W/m^2/K, the maximum heat flux between the vessel and the ambient air can be estimated:

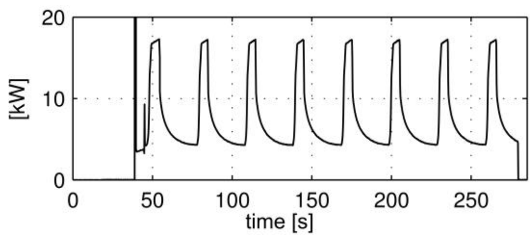
$$\left|Q_{vess}\right|_{\infty} = \alpha \cdot A_{vess} \cdot \Delta\vartheta \approx 23\text{W} \quad (21)$$

Compared to the rated power of 15 kW, the expected heat flux over the vessel surface is in fact negligible.

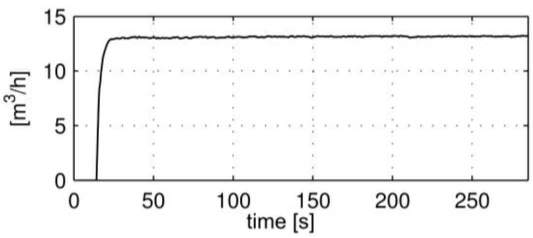
5 CONCLUSION

A model based approach for the evaluation of the energy equivalent of compressed air in a machine tool environment has been introduced. The application and validity of the approach have been demonstrated by measurements on a test system. The most sensitive parameters in Equation (15), are the compressor efficiency and the duty cycle, followed by the coolers energy efficiency ratio and the compression ratio. This observation is consistent with recommendations for compressed air system improvements [2, 4, 5, 8]. Hence, selection of the right energy equivalent is dependent on the available compressed air systems and degree of system integration. Selection of an equivalent should be done for each system individually. For high efficient systems in general, the equivalent is within the range of 0.11 and 0.15 kWh/m^3, dependent on the compression level. For different levels of system integration, this value may change within ±20 % of the value above. For smaller systems, although state of the art, significant higher electrical equivalents must be assumed. Leakage is an important topic as well. Given the situation of the measurement setup, a leak of 0.5 mm^2 would cause a 30 % higher energy equivalent. The quantification of leakage in a shop floor environment is a challenging task, which is not discussed here. Interested readers are referred to publications such as [26] or [27].

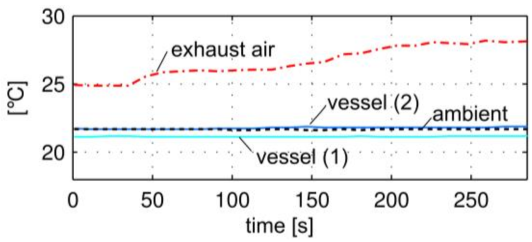
In relation to measurement and monitoring applications the given approach and validation confirms the applied energy equivalent for energy efficient compressors without system integration. Compared to other compressed air energy equivalents, the given approach enables the quantification of heat loss treatments and savings through system integration. Furthermore it enables a more accurate energy equivalent for monitoring purposes on specific compressor types and configurations, without any measurement needed. This offers a significant advantage in the case of an assessment, where no direct measurement of the air compressor is possible.



(a)



(b)



(c)

Figure 3: Cut out of the measurement results; with compressor power (a), compressed air consumption (b) and temperatures (c). The measured temperatures are ambient air (dashed), exhaust air of the fan (dash-dotted) and the vessel surface temperature at two locations (solid).

6 REFERENCES

[1] ISO/DIS 14955-1 Machine tools, 2012, ISO, International Organization for Standardization, Environmental evaluation of machine tools -- Part 1: Design methodology for energy-efficient machine tools.

[2] R. Saidur, N. A. Rahim, and M. Hasanuzzaman, 2010, A review on compressed-air energy use and energy savings, Renewable and Sustainable Energy Reviews, 14: 1135-1153.

[3] C. Yuan, T. Zhang, A. Rangarajan, D. Dornfeld, B. Ziemba, and R. Whitbeck, 2006, A Decision-Based Analysis of Compressed Air Usage Patterns in Automotive Manufacturing, Journal of Manufacturing Systems, 25: 293-300.

[4] J. Hütter, 2008, Effiziente Druckluftproduktion, presented at the International Rotating Equipment Conference, Düsseldorf.

[5] W. Gauchel, 2006, Energy-saving pneumatic systems, Ölhydraulik und Pneumatik, 50: 1-22.

[6] A. Gontarz, L. Weiss, and K. Wegener, 2011, Evaluation Approach with Function-Oriented Modelling of Machine Tools, presented at the 1st International Conference on Sustainable Intelligent Manufacturing, Leiria, Portugal.

[7] A. Gontarz, L. Weiss, and K. Wegener, 2010, Energy Consumption Measurement with a Multichannel Measurement System on a machine tool, presented at the International Conference on Innovative Technologies IN-TECH 2010, Prag.

[8] Energie-Schweiz, 2006, Infoblatt Drucklufterzeugung, ed: Druckluft effizient / Druckluft Schweiz / Frauenhofer ISI, Karlsruhe.

[9] B. Joseph, 2004, Compressed Air Supply Efficiency, in Proceedings from the 26th Industrial Energy Technology Conference, Huston, TX.

[10] M. D'Antonio, G. Epstein, S. Moray, and C. Schmidt, 2005, Compressed Air Load Redution Approaches and Innovations, in Proceedings of the 27th Industrial Energy Technology Conference, New Orleans.

[11] DIN 1343 Referenzzustand, Normzustand, Normvolumen; Begriffe und Werte, 1990, G. I. f. S. (DIN).

[12] C. Schmidt and K. Kissock, 2005, Modeling and Simulation of Air Compressor Energy Use, in ACEEE Summer Study on Energy in Industry, West Point:1-12.

[13] P. Harris, S. Nolan, G. E. O'Donnell, and C. Meskell, 2013, Optimizing Compressed Air Systems Energy Efficiency - The Role of Flow Metering and Exergy Analysis, presented at the 20th CIRP International Conference on Life Cycle Engineering, Singapore.

[14] A. Gontarz, N. Jufer, J. Bathelt, L. Weiss, and K. Wegener, 2011, Determination and Evaluation of CO2 AS A Sustainable Performance Measure on the Basis of a Typical Lathe, presented at the 1st International Conference on Sustainable Intelligent Manufacturing, Leiria, Portugal.

[15] A. Gontarz, S. Züst, L. Weiss, and K. Wegener, 2012, Energetic machine tool modeling approach for energy consumption prediction, presented at the 10th Global Conference on Sustainable Manufacturing, Istambul, Turkey.

[16] P. Harris, G. E. O'Donnell, and T. Whelan, 2010, Model-Based Predictive Consumption of Compressed Air for Electro-Pneumatic Systems, in 36th International MATADOR Conference:405-408.

[17] P. Harris, G. E. O'Donnell, and T. Whelan, 2012, Modelling and identification of industrial pneumatic drive systems, International Journal of Advanced Manufacturing Technology, 58: 1075-1086.

[18] P. Harris, G. E. O'Donnell, and T. Whelan, 2012, Energy Efficiency in Pneumatic Production Systems: State of the Art and Future Directions, presented at the 19th CIRP International Conference on Life Cycle Engineering, Berkeley.

[19] K. Hirano, S. Shida, T. Tominaga, and S. Kitaichi, 2010, Development of a high efficient fual compressor for air consitioner, presented at the International Compressor Engineering Conference, Purdue.

[20] H. Recknagel, 2007, Taschenbuch für Heizung und Klimatechnik – einschliesslich Warmwasser- und Kältetechnik., 73 ed.: Oldenbourg Industrieverlag, München.

[21] Siemens, 2010, DESIGO-Energieeffiziente Applikation: AirOptiControl, Siemens Schweiz AG BT.

[22] M. Miara, D. Günther, T. Kramer, T. Oltersdorf, and J. Wapler, 2011, Wärmepumpen Effizienz - Messtechnische Untersuchung von Wärmepumpenanlagen zur Analyse und Bewertung der Effizienz im realen Betrieb, Frauenhofer-Institut für Solare Energiesysteme, Freiburg.

[23] B+B-Sensors. 2013. Technical Notes Thermocouples. Available: http://www.bb-sensors.com/

[24] M. J. Moran, H. N. Shapiro, D. D. Boettner, and M. Bailey, 2010, Fundamentals of engineering thermodynamics: Wiley.

[25] Kaeser, 2011, Schraubenkompressoren Serie SK, ed. Kaeser Kompressoren AG, Coburg, Germany.

[26] S. Dudic, I. Ignjatovic, D. Šešlija, V. Blagojevic, and M. Stojiljkovic, 2011, Leakage quantification of compressed air using ultrasound and infrared thermography, Measurement, 45: 1689–1694.

[27] A. v. Tonder, 2011, Sustaining Compressed Air DSM Project Savings Using an Air Leakage Management System, Proceedings of the 8th Conference on the Industrial amd Commercial Use of Energy, 133-137.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

11.6 Optimization design of tandem blade rotor of new savonius hydrokinetics turbine model

B. Wahyudi [1], S. Soeparman [2] H.W.M. Hoeijmakers [3]

[1] Mechanical Engineering Department, State Polytechnic of Malang, Indonesia

[2] Mechanical Engineering Doctoral Program, Brawijaya University of Malang, Indonesia

[3] The Laboratory of Engineering Fluid Dynamics, University of Twente, Netherland

Abstract

The Fossil energy crisis prompted many studies to design energy conversion machines from renewable natural sources. One of them is the development of a model turbine savonius with tandem blades for hydropower. For the preliminary research, three model options of tandem blade savonius (TBS) were designed, i.e.: Overlap TBS, Symmetrical TBS, and Convergent TBS. This study aims to determine the best model and the optimal size of the tandem radius (Rt) and clearance blade (e) to produce a maximum pressure drop (ΔP). The method used is to apply CFD simulation and optimization using Response Surface Method (RSM). The best selection model and the result of the optimization design is convergent TBS model with Rt = 27 [mm] and e = 2.75 [mm] capable to generate maximum pressure drop ΔP = 9415.91 [Pa].

Keywords:

Tandem Blade; Savonius; Hydro-kinetic; RSM Optimization; CFD Simulation

1 INTRODUCTION

The effect of fast growing application of computational fluid dynamics (CFD) within the last two decades is the significance of numerical flow simulations in the design of hydraulic machinery that has grown to a considerable extent. At present, CFD simulations can often replace laboratory experiments due to the fact that even complex geometries and entire machines can be modeled. Many researches were conducted to demonstrate the influence of modified Savonius rotor blade geometry parameters such as twist blade, overlap ratio, amount of blade, multi-stage, sweep area, none circular blade, and additional guide blade on the aerodynamic performance of the rotor blade. However, the influence of geometrical design variables and their interactions on the rotor aerodynamic performance was not examined in detail in these works. From this point of view, the present research is focused on suggesting a rotor blade shape design using the numerical optimization method coupled with the statistical approach. Response surface method (RSM) is a collection of statistical and mathematical techniques useful for developing and improving the optimization process, which uses collectively design of experiment, regression analysis, and analysis of variance [1].

The Savonius hydrokinetic turbine is simple geometry and its construction is low-cost to manufacture. It starts rotating at lower speeds as compared to its counterpart hydraulic turbines, having a high starting torque. It produces low noise and can make use of the water river flowing in any horizontal direction to its rotation. However, in spite of these advantages, this turbine faces one main disadvantage of having low efficiency. The preliminary study has been done to choose the best design rotor tandem blade of savonius (TBS). By using the result CFD simulation of the three models i.e.: (a) Overlap TBS, (b) Symmetrically TBS and (c) Convergent TBS as shown in Fig. 1, 2 and 3, one of the best choice to be deeply studied is obtained. The optimum turbine power generation predicted by taking into calculation maximum pressure gap (Δ p) between upstream and downstream is Type Convergent TBS [2].

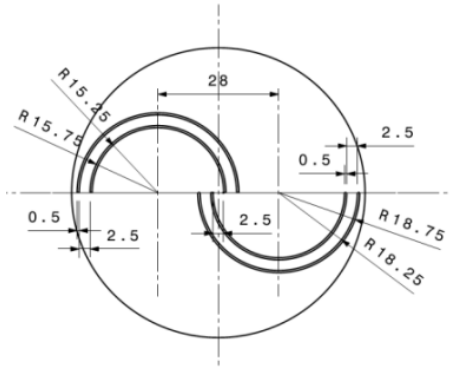


Figure 1: Overlap TBS (Type I)

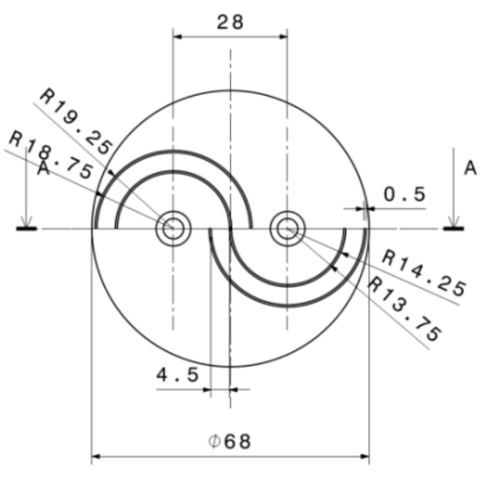


Figure 2: Symmetrically TBS (Type II)

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

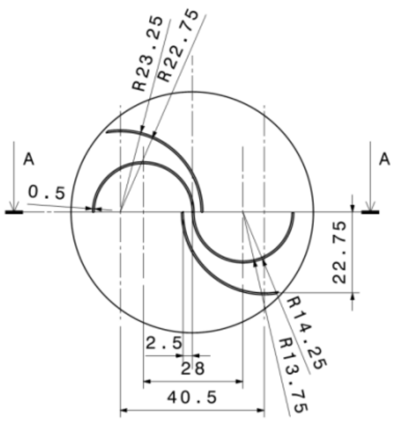


Figure 3: Convergent TBS (Type III)

The Savonious conventional has two pairs of cylindrical blade that look like a letter S which not connected to the middle or with gaps (overlapping) on both ends of the blade that serves as the entry of outflow from the first blade (thrust) to the second blade (return). As shown in Fig. 4, the first blade (advancing blade) got a drag force from the main flow (free flow) while the second blade (returning blade) got a returned force from the opposite direction outflow through the gap (overlap) resulting in a pair off couple force that is able to generate torque and power.

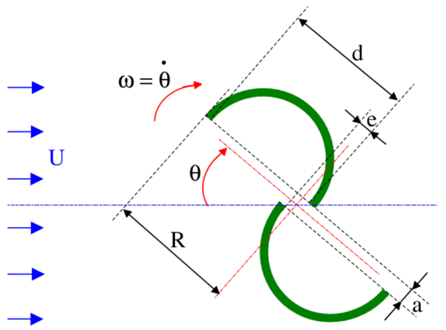


Figure 4: Original Savonius Rotor

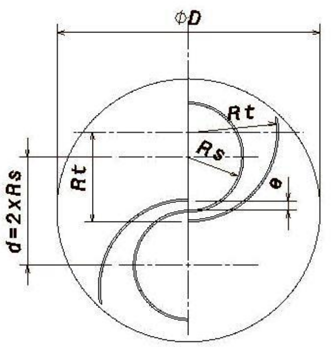


Figure 5: Convergent Tandem Blade Savonius

This paper focuses on optimization using RSM for designing geometry of Convergent TBS as shown in Fig.5 above. Objective of this study is to determine the value of the independent variables that cause the value of maximum pressure gap between upstream and downstream to be optimal. In these experiments, the response variable pressure gap (y) is affected by two independent variables: Radius Tandem Blade " *Rt* " or (x_1) and Clearance Blade "*e*" or (x_2). By using an appropriate model formulation, the value of independent variables (x_1, x_2) which causes maximum pressure gap designation optimal can be obtained.

2. RESPONSE SURFACE METHOD (RSM)

To understand how far the optimum process is influenced by number of variables, it is often necessary for experimental data to be large and takes a long time, which automatically also cost a huge amount. Several statistical and mathematical techniques are often used to make an approach to gain understanding of the optimum conditions of the process or design without requiring too much data. Among the commonly used method is the response surface method (RSM).

RSM is a set of mathematical and statistical techniques that are useful for analyzing problems where several independent variables affect the response variable and the ultimate goal is to optimize the response. The basic idea of this method is the use of statistical experimental design assisted to find the optimal value of the response. This method was first proposed in 1951 and has been used extensively in both the research and industrial applications until today. For example, by constructing a mathematical model, researchers can determine the value of the independent variables that lead to an optimal value of the response variable.

The first step of the RSM is to find a relationship between the response variable y with xi independent through a first order polynomial equation (model order I). Independent variables denoted by x1, x2, ..., xk. These variables are assumed to be controlled by the researcher and the influence response variable y is assumed as a random variable. If the response is well modeled by a linear function of the independent variables xi, the function approximation of the model order I are:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon \qquad (1)$$

with, y : dependent variable (response)

xi : factors that influence response variables, i = 1, 2, k

ε : residual component (error) which is random and distributed identical and independent (Independent Identically Distributed-IID) Normal distribution with the average value of 0 and variance σ2. In mathematically expressed by ε ≈ IID Normal (0, σ^2).

Furthermore, at the condition near the response, the second order model (order II) or more normally required to approximate the response due to the curvature in the surface. In many cases, the model order II two expressed in equation (2) is considered sufficient.

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i}\sum_{j} \beta_{ij} x_i x_j, i < j \qquad (2)$$

Analysis of the response surface fitting Order II is often referred as the canonical analysis [1]. Least squares method is used to estimate parameters on the approximation functions. The subsequent RSM analysis can be used for surface fitting. If the surface fitting is a good approximation of a function of the response, surface fitting analysis would be equivalent with the actual analysis systems.

Analysis of variance and regression analysis are the statistical techniques to estimate regression coefficients in the quadratic polynomial model and also yield a measure of uncertainty in the coefficients. One of the important statistical parameters is the coefficient of determination, R^2 which provides the summary statistic that measures how well the regression equation fits the data. It is given as:

$$R^2 = \frac{SSR}{SSTO} = 1 - \frac{SSE}{SSTO} \quad (3)$$

where SSTO is the total sum of squares, SSR is the regression sum of squares, and SSE is the error sum of squares. From the inspection of Equation (3), it is found that $0 \leq R^2 \geq 1$. However, a large value of R^2 does not necessarily imply that the regression model is a good one. Adding a variable to the model always increases R^2, regardless of whether the additional variable is statistically significant or not. Thus, it is possible for the models that have large values of R^2 to yield the poor predictions of new observations or estimates of the mean response. Because R^2 always increases as we add terms to the model, the adjusted -R^2 statistic parameter, R^2adj defined below is frequently used.

$$R^2_{adj} = 1 - \frac{SSE/(n_s - n_{rc})}{SSTO/(n_s - 1)} = 1 - \left(\frac{n_s - 1}{n_s - n_{rc}}\right)(1 - R^2) \quad (4)$$

In general, the adjusted-R^2 statistic does not always increase as variables are added to the model. In fact, if unnecessary terms are added, the value of $R^2\ adj$ often decreases.

It is important to determine the value of each regression variable in the regression model, because the model may be effective with the inclusion of additional variables or with the deletion of the variables already in the model. The test statistic (t-statistic) for testing the significance of any individual regression coefficient is

$$t = \frac{c_j}{\sqrt{\sigma^2 C_{jj}}}, \qquad j = i, \dots\dots, n_{rc} \quad (5)$$

Where is the estimation of variance and C_{jj} is the diagonal element of $(X^TX)^{-1}$ corresponding to c_j.

3. DEVELOPMENT OF SAVONIUS ROTOR

Currently, the Savonious turbine has been developed with various modifications with the purpose of improving their performances. Cesar Humberto [3] combined the simulation and optimization method using genetic algorithm (GA) to design modified savonius rotor. Browsing point of optimization by using Polar Coordinate system for changing the shape of original rotor savonius combining with Banesh rotor produce a new shape of rotor savonius which is more efficient.

Menet, J .[4] has modified the savonius rotor which only changes the position of an off-set the second pair of rotor blades, now has three geometric parameters, namely: (1) primary overlap (e), secondary overlap (e '), and the angle between the axis blades (β). The result is relatively expected s new rotor induces maximum value of static torque is much higher than those obtained with the conventional rotor. However, they found low values and negative torque when an angle β has large variations. Overall, the average value of the torque increased to Cm = 0.48 or 60% more than the conventional rotor.

Fujisawa and Gotoh [5] has published a study comparing experimental results with a numerical study also using the discrete vortex method. He concluded that the numerical calculations were adequate to “predict the basic features of the variation in flow fields with rotor angle”. Nevertheless, the procreation of the flow field around a stationary rotor was poor, and Fujisawa supposed that it was due to false assumptions used in the calculations. Sometimes, some visualizations of the flow in and around the rotor are proposed, but with a poor description of the physical phenomena. Fujisawa [6] also presented a exclusive description of the Visualization study of the flow in and around a of the conventional Savonius rotor, they conclude that the overall pressure coefficient decreased due to the effect of the circulation generated by rotor rotation. This is a phenomenon of circulation persists in revolving condition compared with stationary rotor, where the flow through the overlap is reduced due to backflow. The flow is expected to reduce the effect of pressure recovery on the back side of blade behind because of the pressure distribution near the overlap.

Kamoji et al. [7] improved the coefficient of power and obtained uniform coefficient of static torque. To achieve these objectives, the rotors are being studied with and without central shaft between the end plates. Experimental tests in a closed jet wind tunnel on modified form of the conventional Savonius rotor with the central shaft have the value of Cp = 0.32. They studied the effect of geometrical parameters on the performance of the rotors in terms of coefficient of static torque, coefficient of torque and coefficient of power. The parameters studied are overlap ratio, blade arc angle, aspect ratio, and Reynolds number.

Performance of Savonius hydro-kinetic turbine has dependence with the principle to generate drag forces is formulated by $F = ½. ρ. A.U^2$, thus optimizing torque and power turbine formation is highly dependent on the blades swept area (A) and velocity of fluid (U). Therefore, this paper introduced a new concept design of Savonius rotor by broadening swept area of tandem blade that can increase drag force production on the blade as shown as Fig. 3. To achieve the maximum power generation using convergent TBS rotor design, we use CFD simulation and RSM to realize optimum Radius Tandem Blade (Rt) and Clearance Blade (e) as independence variable.

4. CFD SIMULATION

By adapting the law of Navier-Stokes model of rotation frame, the equations governing the behavior Savonious hydrokinetics turbines will be used in this study. The equations rule the behavior of fluid flow including conservation of mass (eq. 6) and momentum equations (eq. 7). Two types of acceleration in the momentum equation representing two Savonious hydrokinetics turbine rotation are the Coriolis acceleration, ($2\tilde{\omega} \times \bar{\upsilon}_r$) and the centripetal acceleration ($\tilde{\omega} \times \tilde{\omega} \times \hat{r}$).

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \bar{\upsilon}_r = 0 \quad (6)$$

$$\frac{\partial}{\partial t}(\rho \bar{\upsilon}_r) + \nabla . (\rho \bar{\upsilon}_r . \bar{\upsilon}_r) + \rho(2\tilde{\omega} \times \bar{\upsilon}_r + \tilde{\omega} \times \tilde{\omega} \times \hat{r})$$
$$= -\nabla p + \nabla \tau + F \quad (7)$$

In this equation, $\hat{r}$ is the radial position of the rotating domain forms, $\tilde{\omega}$ domain is the angular velocity of the rotor, $\bar{\upsilon}_r$ is the relative velocity, p is the static pressure, τ is the stress tensor and F represents the external body force. Adopting a combined formulation in cylindrical coordinates and Cartesian, in order to simulate two separate regions of the domain, i.e. inflows rotate the rotor-stator and external. Standard K-ε model, Eq. (8) and (9), is used to simulate the turbulence in the flow field [8]. They are coupled to the Navier-Stokes equations although included in the convection zone. It is a widely used and provides sufficient accuracy and worthy to represent the various types of flow. K-ε model is a two-equation models involving turbulent kinetic energy, k, and the dissipation rate, ε, as follows,

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) =$$

$$\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \quad (8)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=$$

$$\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_K+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \quad (9)$$

$$\mu_t=\rho\, C_\mu\, \frac{k^2}{\varepsilon} \quad (10)$$

In this model, G_k represents the generation of turbulence kinetic energy due to the velocity gradient, whereas G_b describe the generation of turbulence kinetic energy due to buoyancy, and Y_M is the contribution of the fluctuating dilatation to the overall dissipation rate. Variable σ_k and σ_ε are Prandtl numbers for the turbulent with value of k = 1.0 and ε = 1.3. Constants $C_{1\varepsilon}$ = 1.44 and $C_{2\varepsilon}$ = 1.92. Turbulent viscosity (or Eddy current), μ_t is computed by combining k and ε as shown in Eq. 10, where Cμ = 0.09.

This equation will be used to predict fluid flow through a turbine that will improve its performance.

By using simulation software ANSYS Release 14.5 it's the following boundary conditions that have been applied. The stationary domain has a free stream velocity. The hydrodynamic pressure conditions are applied and the initialization is done. Inlet and Outlet are default boundary conditions in simulation software. Inlet requires the speed of inlet velocity of water and the outlet requires the relative pressure, 1.0132 x 105 [Pa], at the initial conditions. The blade surfaces are enabled a "wall" condition. This condition enables the calculation of properties such as force, torque on the surface. Once the domains have been specified, a default fluid-fluid interface is detected between the rotating and stationary domain.

A two-dimensional view of the rotor model was considered. It is because the rotor blades rotate in the same plane as the approaching water flow stream. The computational domain was discretisized using two-dimensional unstructured mesh (triangular mesh). The left boundary had Velocity Inlet condition while the right boundary had Outflow condition. The top and bottom boundaries for the open channel sidewalls had symmetry conditions. The moving wall condition was employed for the rotor model to study the effect of fluid motion in and around the rotating Savonius rotor. The dimensions of the computational domain were 500 mm in length and 75,5 [mm] in width, which were also similar to the experimental conditions. For the various model conditions, the geometry of the rotor was changed and accordingly different meshes were generated for each condition.

Steps in the simulation solutions consist of:

1. Solver (Pressure Based, Steady, 2D)
2. Viscous Model: Standard k-epsilon (k-ε) / Near-Wall Treatment: Standard Wall Functions
3. Material: Water (μ = 1.002x10-3 [kg/m-s], ρ= 1.000 [kg/m3])
4. Operating conditions: Atmospheric Pressure (1.0132 [bar])
5. Boundary Conditions:
   - Inlet: Velocity Inlet
   - Sides: No slip wall
   - Blades: Stationary Wall
   - Outlet: Outlet
6. Solution controls:
   - Pressure Velocity Coupling: SIMPLE
   - Discretization: fluids
7. Pressure (Standard) / Inlet Velocity: 1 [m/s]

5. RESULT AND DISCUSSION

In the contour plots as shown at Figure 5, the blade on the left hand side is the returning blade and that on the right hand side is the advancing blade. The contour plots predict the variations in velocity and pressure in various regions near the blades within the flow domain. It can be observed from the pressure contour plots that pressure gap occur across the rotor from upstream to downstream side. This pressure gap indicates power extracted by the rotor causing its rotation [5]. The static pressure on the convex side of both the blades can be observed to be lower than those on the concave side of the blades; in fact, a region of negative pressure exists on the convex side of the blades. This occurs due to the high flow velocity over the convex side of the blades. As a result, a pressure difference acts across the concave and convex side of the blades, which provide the necessary torque for causing rotation of the blades.

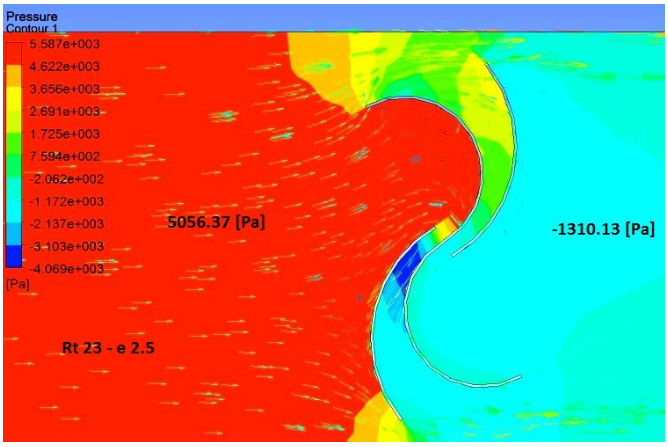


Figure 6: CFD simulation demonstrate the effect of Rt = 23[mm] and e = 2.5[mm] caused Δ P = 6366.5 [Pa]

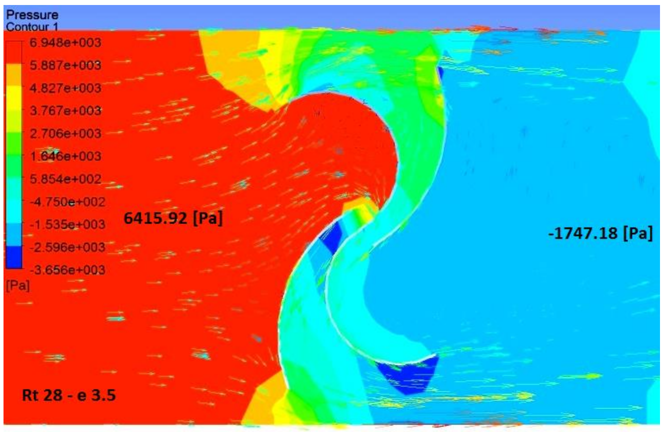


Figure 7: CFD simulation demonstrate the effect of Rt = 28 [mm] and e = 32.5 [mm] caused Δ P = 8163.1 [Pa]

Table 1: Central Composite Design Using Minitab R 14

Run Order	PtType	Blocks	Rt (mm)	e (mm)	ΔP (Pa)

1	1	1	23.0000	2.50000	6366.50
2	1	1	28.0000	2.50000	9134.91
3	1	1	23.0000	3.50000	5265.32
4	1	1	28.0000	3.50000	8163.10
5	-1	1	21.9645	3.00000	5039.54
6	-1	1	29.0355	3.00000	8817.03
7	-1	1	25.5000	2.29289	8721.59
8	-1	1	25.5000	3.70711	8835.92
9	0	1	25.5000	3.00000	8951.22
10	0	1	25.5000	3.00000	8951.22
11	0	1	25.5000	3.00000	8951.22
12	0	1	25.5000	3.00000	8951.22
13	0	1	25.5000	3.00000	8951.22

Table 2: Regression Coefficient Order II

Term	Coef.	SE Coef.	T	P
Constant	8951.2	187.9	47.626	0.000
RADIUS TANDEM BLADE	1376.0	148.6	9.261	0.000
CLEARANCE	-238.9	148.6	-1.608	0.147
RTB*RTB	-1166.7	159.3	-7.322	0.000
CLEARANCE*CLEARANCE	-241.5	159.3	-1.516	0.168

S = 420.3 R-Sq. = 94.7% R-Sq.(adj.) = 92.0%

To discuss the results of RSM optimization, as shown in Table 1 presented the CFD simulation data of rotor convergent TBS model using variable tandem radius (Rt) and Blade Clearance (e) with the lowest value of 23 mm - 2.5 mm and the highest 28 mm - 3.5 mm, both pressure gap indicates that each Δp = 6366.5 (Pa) and Δp = 8163.1 (Pa). The two independent variables were considered as variables that affect maximize pressure gap (y), i.e., Radius (x_1) and Clearance (x_2). Experimental design used in the DoE is three-level factorial design (3k) using the Central Composite Design (CCD). The first step has been tested using a linear regression equation (Order I) with obtained R-square is only 54% and a P-value> 0.05 so it does not show any significance of the model.

Furthermore, similar test attempted to Order II model equations (linear + square) obtained a significant regression coefficient. To check the significance of the second-order model, it can be seen that p-value = 0.000 is less than the significance level α = 5%, see also that the independent variables x_1 made a significant contribution in the model, but x_2 is not significant. But, Overall this model it is able to demonstrate the high value of R-square = 94.7 % in Table 2, which means that the regression equation model is consistent with the real condition of the model studied. The model regression equation (11) is expressed:

$$\Delta P = 8951.2 + 1376\,(Rt) - 238.9\,(e) - 1166.7\,(Rt)^2 - 241.5\,(e)^2 + \varepsilon$$

After the optimization model has determined, the next step is to determine the conditions optimum of significant factors. From the contour plot of the image below, it can be concluded that the image does not have a stationary point. Consequently that calculation of the stationary point and surface characteristics of the response is not necessary. The result of response (ΔP) optimization will be obtained after value of (Rt) and (e) which substituted into the model equation above with constant value of Rt = 27 [mm] and variable e = 2.5 [mm] ÷ 3.5 [mm]. By using Minitab Software, it is more simple to obtain the result of peak point in the curvature as shown in Fig. 8 which show optimal value of Rt = 27 [mm] and e = 2.75 [mm] with response of maximum ΔP = 9415.91 [Pa].

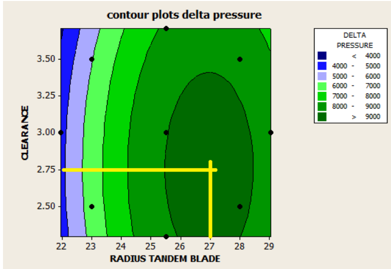


Figure 8: Contour Plot

6. CONCLUSION

Finally, with applied CFD simulation and optimization using RSM, we are able to assist design engineering of the critical part of convergent tandem blade of Savonius rotor that capable to generate maximum power on hydrokinetic turbine model. The result of design optimization of Savonius tandem blade is showed in Fig. 9 below with Rt = 27 [mm] and e = 2.75 [mm]. By using an appropriate model formulation eq. 11, the result value of independent variables "Rt" and "e" which causes maximum pressure gap designation optimal can be obtained which would be produce power maximum.

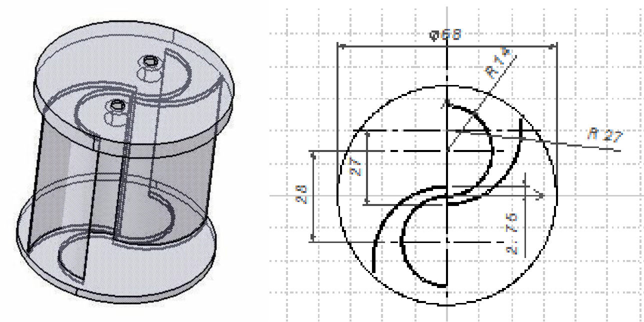


Figure 9: The result design of convergent TBS Rotor

7. REFERENCES

[1] Montgomery, D. C., 1984, Design and Analysis of Experiments, John Wiley & Sons, Canada.

[2] Bagus Wahyudi, et al., 2013, A Simulation Study of Flow and Pressure Distribution Patterns in and around of Tandem Blade Rotor of Savonius (TBS) Hydrokinetic Turbine Model, Journal of Clean Energy Technologies, Vol. 1, No. 4, July, p.p. : 286-291.

[3] Cesar Humberto, 2008, Optimization of the efficiency of a Savonius wind turbine for urban media using Genetic Algorithm, Master Thesis, Instituto Technologico De Monterrey.

[4] Menet, J, 2004, Increase in the Savonius Rotors Efficiency via a Parametric Investigation,. Available on http://www.2004ewec.info/files/23_1400_jeanlucmenet_01.pdf

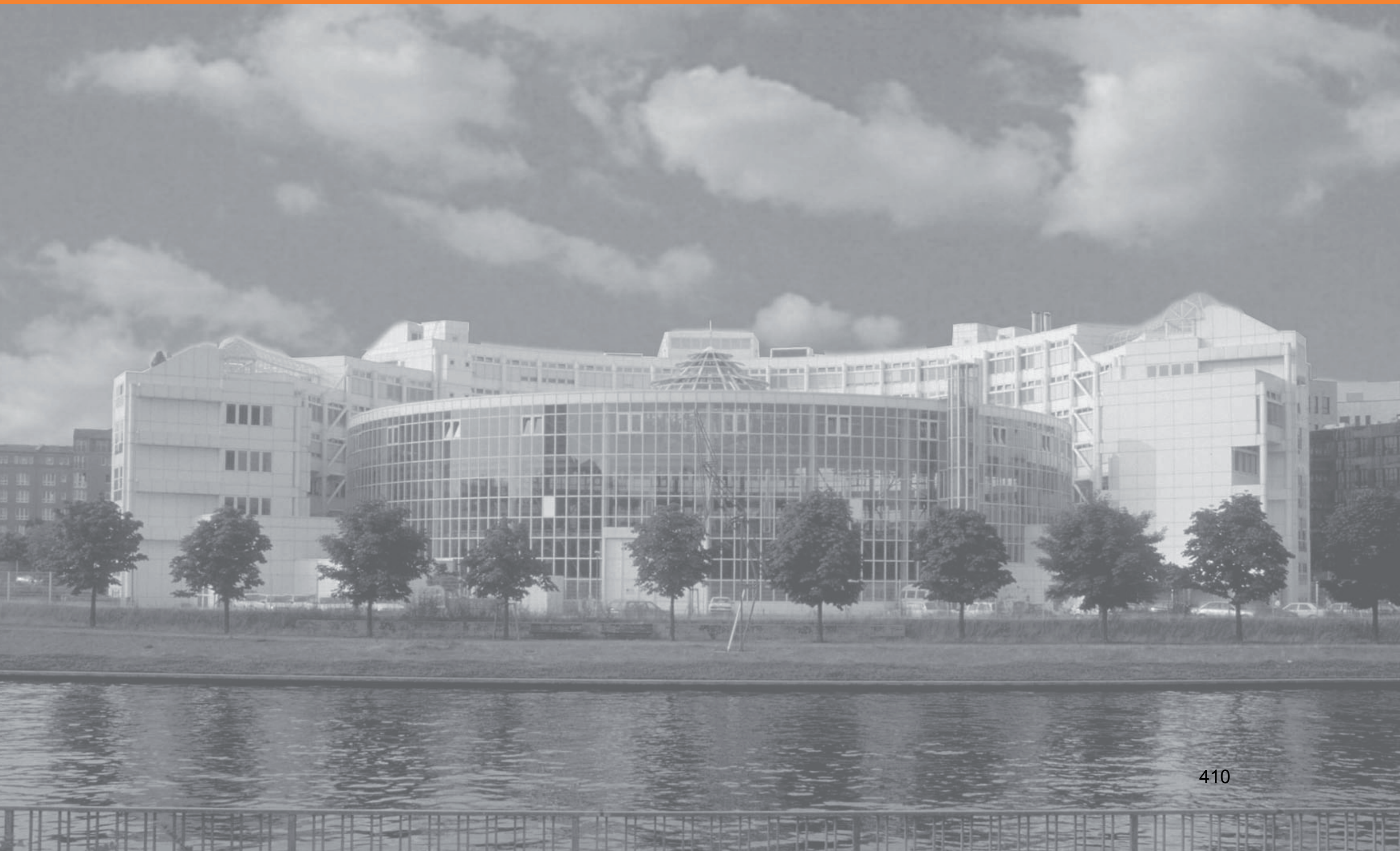
[5] N . Fujisawa and F. Gotoh, 1992, Visualization study of the flow in and around a Savonius rotor, Exp. in Fluids,12(6), pp. 407-412

[6] N. Fujisawa, 1996, Velocity measurements and numerical calculations of flow fields in and around Savonius rotors.' J. Wind Eng. Ind. Aero.; 59 , pp.: 39-50.

[7] M.A. Kamoji, S.B. Kedare, S.V. Prabhu, 2009, Experimental investigations on single stage modified Savonius rotor, Applied Energy, vol. 86, no. 7-8 pp.: 1064-1073.

[8] Pope Kevin, 2009, Performance Assesment of Transient Behaviour of Small Wind Turbines, Master Thesis in Applied Science, University of Ontario Institute of Technology.

Session 12
Material



GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

12.1 Evaluating the performance of selected constitutive laws in the modeling of friction stir processing of Mg Alloy AZ31b – Toward a more sustainable process

A. H. Ammouri, A. H. Kheireddine, R. F. Hamade

Department of Mechanical Engineering, American University of Beirut (AUB), Beirut, Lebanon

Abstract

In modeling friction stir processes (FSP), the choice of material constitutive law directly influences the state variables output which, in turn, is critical in producing uniform metal sheets. This is especially true in AZ31b due to the temperature sensitivity of magnesium. Different constitutive laws tend to produce wide variations in the values of predicted flow stress as well as in temperature profiles especially in the stir zone. Capturing accurate state variables would improve the controllability of friction stir processes by providing suitable control models and, thus, contributing to enhanced sustainability of this process. Two constitutive laws widely used in FSP modeling of AZ31b are assessed in this work. We utilize a robust finite element model with fine-tuned boundary conditions. Comparing the output state variables with those from experiments provided for an objective assessment of the capabilities and limitations both constitutive laws over variable ranges of interest.

Keywords:

AZ31b, Material constitutive laws, FEM, Friction stir processing, Sustainability

1 INTRODUCTION

Friction stir processing (FSP) is a microstructure modification processing technique initially developed in 2001 by Mishra and Mahoney [1] and is based on similar principles to those of friction stir welding (FSW). As in FSW, a rotating tool is plunged into the workpiece to be processed and traversed across areas of interest to be modified. Figure 1 illustrates FSP and describes the different zones of the process. The stirred zone (SZ) is the area with the most severe mechanical deformation and frictional heating where the high strain rate and temperatures initiate dynamic recrystallization (DRX). The thermo-mechanically affected zone (TMAZ) is the area surrounding the stirred zone and is subject to both thermal effects and mechanical deformation which deform the original microstructure. The heat-affected zone (HAZ) is subject to thermal effects from the nearby welding zone.

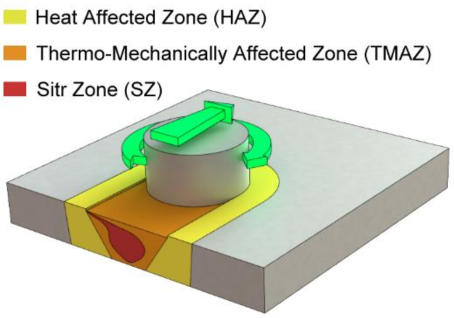


Figure 1: FSP illustration showing affected zones.

Friction stir processes are associated with large strains, moderate to high strain rates, and elevated deformation temperatures [2] with reported values were either results of direct sensor measurements or predictions of numerical simulations. Temperature is the only state variable that can be directly measured and, thus, the values in the literature for temperatures are of high confidence. Such reported temperatures reach up to 95% of the material's melting point [3]. Strains and strain rates are quite difficult to measure directly due to the complexity of the process. Thus, numerical models are typically used for the prediction of these variables. Estimated values of strain are reported to reach values of up to 125.1% [4] and maximum strain rates values to range from 10^1 1/s [5] upwards to 10^3 1/s [6] (assuming identical processing parameters). Most of the reported values were produced after tuning the tool/workpiece interface boundary conditions to produce temperature profiles match those experimentally measured.

Different constitutive laws have been used in the literature to model the material behavior in friction stir processes but with each law suffering from drawbacks and with steep state variables' gradients it was proven difficult for most of these constitutive laws to predict the variables values over the entire range of variation. Evaluated in this work is the performance of two of the more popular material models in friction stir processes. Specifically, the Sellars-Tegart [7] and Johnson-Cook [8] constitutive laws were extensively used in FSW and FSP modeling with each law having advantages in capturing accurate state variables at different regimes of interest .

Both are empirical-based laws that fit experimental mechanical behavior data to mathematical equations. The validity of the models and their applicability to friction stir processing are as good as the ranges of strain, strain rate, and temperature parameters over which the laws were originally fit. The wider the range, the better, supposedly, is the applicability but this would require extensive mechanical testing ranging from tensile/compressive tests on universal testing machines to impact testing (e.g., split Hopkinson bar tests). The reason for adopting these two models is due to their ease of

ISBN 978-3-7983-2609-5

implementation in numerical solvers and the availability of their material constants in the literature for many metals of interest.

This paper presents a numerical-based evaluation for the performance of the Johnson-Cook and Sellars-Tegart material models for FSP of magnesium alloy AZ31b. The importance of this comparison is to provide the reader with a reference on the accuracy of each model for capturing the state variables at different areas of interest in the friction processed zone. This would yield to better numerical simulation results that would, ultimately, enhance the sustainability of the process.

2 THE FE MODEL

A 3D thermo-mechanically coupled FE model was developed using the commercial FEA software DEFORM-3D™ (Scientific Forming Technologies Corporation, 2545 Farmers Drive, Suite 200, Columbus, Ohio 43235 [9]). The meshed model shown in Figure 2 consists of a tool, a workpiece, and backing plate. Both the tool and the backing plate were modeled as rigid un-deformable bodies where only heat transfer was accounted for while the workpiece was modeled as a plastic body subject to both deformation and heat transfer.

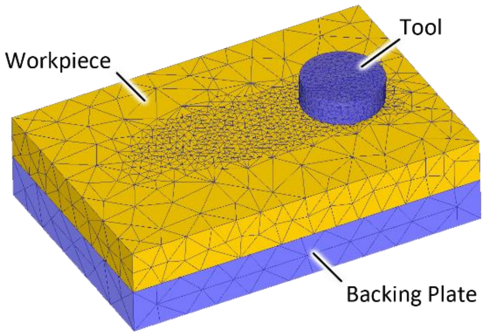


Figure 2: The meshed FEM model used in the simulations

The considered tool had an 18 mm cylindrical shoulder with a 6 mm diameter smooth unthreaded pin that extrudes 6 mm from the bottom of the shoulder. The tool was tilted 3° about the vertical axis in the processing direction to further improve material flow. Both the workpiece and the backing plate had an area of 80x54 mm^2 and a height of 10 mm.

Materials used in the FEM model were H13 steel for the tool, AISI-1025 steel for the backing plate and AZ31b for the workpiece. Table 1 summarizes the different mechanical and thermal properties of AZ31b obtained from literature [10-11].

Tetrahedral elements were used in the FEM model with active local re-meshing triggered by a relative interference ratio of 70% between contacting edges. The tool and the backing plate were meshed for thermal analysis purposes with each containing around 6000 and 5000 elements respectively while the workpiece had around 16000 elements. To further capture the state variables at the tool-workpiece interface, a rectangular mesh control window was applied around the processing area of interest where finer mesh elements were created.

Heat transfer with the environment was accounted for all the three meshed objects with a convective heat coefficient of 20 W/(m^2 ºC) at a constant temperature of 293K. The heat transfer coefficient between the tool-workpiece and backing plate-workpiece interfaces was set to 11 kW/(m^2 ºC) [12].

Friction at the tool-workpiece interface is a significant factor in any FSP/FSW simulation. It is determined that 86% of the heat generated is due to frictional forces [13]. Determination of the friction factor is a daunting challenge due to the variation of temperature, strain rate, and stress. A literature search for identifying suitable expressions of friction coefficient in magnesium alloys revealed that ring upsetting and compressions tests are used for determining the coefficient of friction [14-15]. It is found that the friction factor increases with temperature [16]. However, this increase of friction factor with temperature is valid until the liquidus temperature of AZ31b (630°C) is reached at which the friction drops drastically. Experimental values of the coefficient [17] were entered to the model and then extrapolated by tuning different runs and analyzing state variables. The friction coefficient vs. temperature behavior that was arrived at by tuning in this work is shown in Figure 3 co-plotted on which are the experimental values from [17]. The performance of the utilized FE model along with the assumed friction coefficient was previously validated by the authors [18-19].

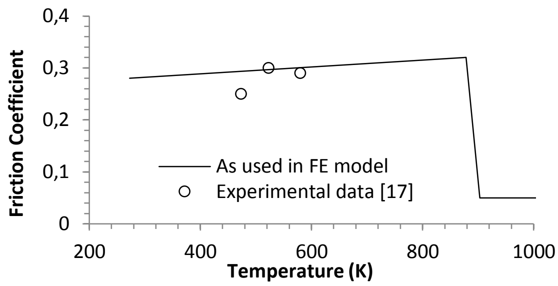


Figure 3: Friction coefficient VS Temperature as used in the FE model; shown compared with experimental [17]

Table 1: Material properties of the utilized AZ31b

Property	Value
Elastic Modulus [10]	44830 MPa
Poisson's ratio [10]	0.35
Coefficient of thermal expansion [10]	2.65×10^{-5}
Thermal conductivity [10]	96 N/(s K)
Heat capacity [11]	2.43 N/(mm^2 C)
Emissivity [11]	0.12

The constitutive laws considered for modeling the material behavior were the Sellars-Tegart and the Johnson-Cook laws.

The Sellars-Tegart material model considers the material to be rigid visco-plasic where flow stress ($\bar{\sigma}$) is related to temperature (T) and strain rate ($\dot{\bar{\varepsilon}}$) according to

$$\bar{\sigma} = \frac{1}{\alpha}\sinh^{-1}\left[\frac{1}{A}\dot{\bar{\varepsilon}}e^{\left(\frac{\Delta H}{RT}\right)}\right]^{\frac{1}{n}} \quad (1)$$

Where A, α, and n are material constants, ΔH being the activation energy, and R the universal gas constant.

The Johnson-Cook model accounts for the effects of strain (ε), strain rate ($\dot{\varepsilon}$) and temperature (T) according to

$$\bar{\sigma} = \left(A + B\bar{\varepsilon}^{n}\right)\left(1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right)\left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^{m}\right) \quad (2)$$

Where *A*, *B*, *C*, *n*, and m are material constants. T_{room} and T_{melt} being the room and melting temperatures. $\dot{\varepsilon}_0$ is used to normalize the strain rate and is equal to $1 s^{-1}$

For preserving the authenticity of the comparison, the material constants of both equations (1) and (2) were determined by fitting the equations to experimentally collected stress strain curves of tensile tests carried out for this purpose. The ranges of temperatures and strain rates of the performed tests were 25-300 °C and 10^{-4}-10^{-1} s^{-1} and the specimen used was according to ASTM E2448-11.

The material constants of AZ31b for the Sellars-Tegart and Johnson-Cook models are described in tables 2 and 3 respectively.

Table 2: Constants of the Sellars-Tegart model for AZ31b [13]

A	*α*	*n*
27.5	0.052	1.8

Table 3: Constants of the Johnson-Cook model for AZ31b [20]

A	*B*	*n*	*C*	*m*
224	380	0.761	0.012	1.554

The simulation process parameters for the traverse phase were 1000 RPM for the tool rotational speed and 90 mm/min for the tool traverse speed. These parameters were selected according to optimum processing conditions for AZ31b which were determined by the authors [18]. For each constitutive model, simulations were run and the state variables were determined and logged for comparison.

3 RESULTS AND OBSERVATIONS

For each of the constitutive models, a complete traverse FSP pass was simulated where the tool starts from a pre-set position inside a groove in the workpiece at the final position of the plunging phase. Plunging phase wasn't simulated in this work since our only interest is in the traverse phase which will have the most significant effects on the state variables in the processed area.

After the conclusion of the simulations, strains, temperatures and stresses of a cross-section passing through the center of the tool were captured and the results were plotted accordingly.

For systematic comparison all the differences between the predicted state variables will be calculated as percentage of the Sellars-Tegart results.

3.1 Strain comparison

Strain output values for both constitutive models are shown in Figure 3. The trend and levels of strain are of the same order of magnitude for both cases as one would expect given that FEM solves initially for deformations and their derivatives, the strains independently of the stress. The average reported total Von Mises strain values for the Johnson-Cook and Sellars-Tegart models were 0.91 and 1.08 mm/mm respectively. These values are of the same order of magnitude of those reported in the literature [5].

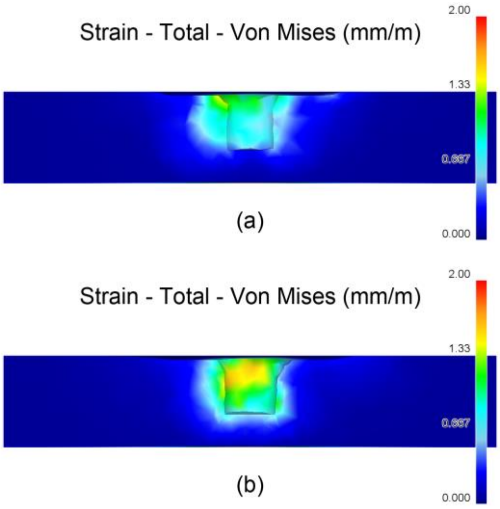


Figure 3: Effective strain (mm/mm) for the (a) Sellars-Tegart and (b) Johnson-Cook; 1000 RPM, 90 mm/min

The ~16% difference between the maximum reported values of both constitutive models can be due to the inter-object boundary condition variation during the re-meshing process.

Appreciable values of strain was only observed in the stir zone and at the interface between the TMAZ and the stir zone.

The maximum strain value was observed on the advancing side of the processed area (the left side) where the tool rotation and workpiece translation oppose each other causing rise in state variables at the tool/workpiece interface.

3.2 Temperature comparison

Temperature snapshots of the processed area cross-section are shown in Figure 4. The trend for both models differed slightly for the temperature state variables. Higher temperature profile values can be noticed for the Johnson-cook model. The maximum reported value for the temperature were 452 ^{0}C at the tool/workpiece for the Sellars-Tegart model and 596 ^{0}C for the Johnson-Cook model (which is close to AZ31b liquidus temperature).

The Johnson-Cook model values of the maximum reported temperature exceeded that of the Sellars-Tegart model by 31.8%. The temperature profile however seems to extend more towards the TMAZ and HAZ in the case of Johnson-Cook.

It was also observed that the thermal effects in the Johnson-Cook model reached the bottom of the workpiece where values of 420 ^{0}C were measured compared to values of 329 ^{0}C for the Sellars-Tegart model. This discrepancy will be discussed in the conclusion section.

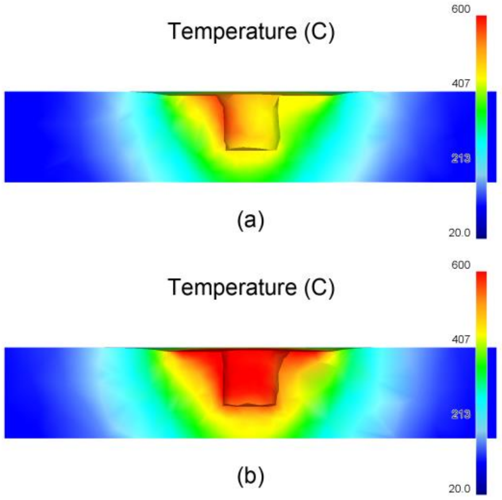


Figure 4: Temperature (^{0}C) for the (a) Sellars-Tegart and (b) Johnson-Cook; 1000 RPM, 90 mm/min

3.3 Stress comparison

The reported total Von Mises stress values for the simulations are described in this section where major discrepancies were observed between the model predictions. The maximum reported values for the Sellars-Tegart model were 303 MPa compared to 524 MPa for those of the Johnson-Cook model. For proper comparison the color scales of both models was set at the ultimate stress of AZ31b at 25^{0}C (330 MPa).

The Johnson-Cook model over predicted stress values of those of the Sellars-Tegart by 73% in the stir zone. A different trend of stress distribution was observed for the two test cases which can be clearly seen in Figure 5.

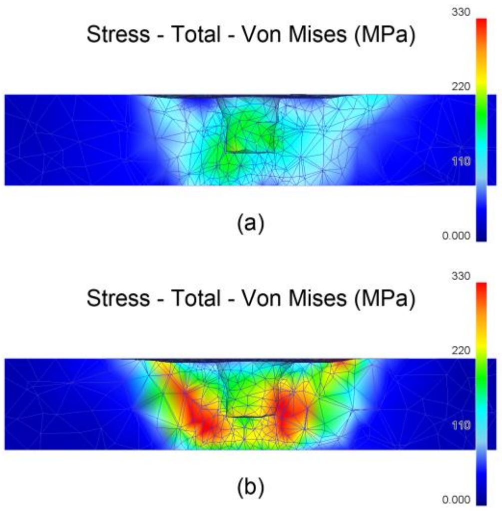


Figure 5: Effective stress (MPa) for the (a) Sellars-Tegart and (b) Johnson-Cook; 1000 RPM, 90 mm/min

4 CONCLUSIONS

The following findings may be concluded from the results and observations described in Section 3:

1. Strain values are found to be practically independent of whether the Sellars-Tegart constitutive material law (equation (1)) or the Johnson-Cook law (equation (2)) is used. This is due mainly to how FEM calculates strains from differentiating deformations independently of the constitutive laws used. Strain values are a strong function of other important factors that need to be defined such as the boundary conditions set between tool and work.
2. The Johnson-Cook law (equation 2) appears to over predict the values of strain in the stir zone where strains exceed saturation values whereas the strain-independent Sellars-Tegart law (equation 1) accounts for saturation. This increased stress estimates would also result in increased temperature predictions in the case of the Johnson-Cook model compared with the Sellars-Tegart law.
3. The Sellars-Tegart constitutive material law (equation 1) is incapable of capturing the process parameters outside the stir zone especially due to its inability to capture strain hardening in areas with low strains such as the TMAZ.

One can deduce from the above findings that each constitutive law has its advantages over the other in specific areas of the processed zone. If the main interest is in capturing the stir zone state variables then the Sellars-Tegart would be the model to work. Johnson-Cook on the other hand should be used for assessing the TMAZ and HAZ since it captures better state variables in these zones.

5 SUMMARY

A robust FE numerical model was used to compare the performances of two different material constitutive laws used in the friction stir processing of magnesium alloy AZ31b. Both laws resulted in marked variations in the estimated values of the output state variables namely stress and temperature. Such variations were especially noted across the different regions within the friction processed areas. Each of the two law shows advantages over the other depending on the processing conditions. The Sellars-Tegart model yielded more representative values of state variables in the stir zone whereas the Johnson-Cook model yielded more representative values in the TMAZ. The high strain values observed in the stir zone resulted in stress over-prediction when using the Johnson-Cook law due to the strain hardening constituent of the model. The lack of strain hardening in the Sellars-Tegart law results in constant stress values at different strains which results in large errors in areas with low strains. Care should be taken when choosing which constitutive law to be used while modeling friction stir processes depending on the accuracy of the state variable prediction required at a desired area of interest. The accuracy of the captured state variables is a key factor to improve the controllability of friction stir processing by providing suitable control models which contribute to enhanced sustainability of the process.

6 ACKNOWLEDGMENTS

This publication was made possible by the National Priorities Research Program (NPRP) grant # 09-611-2-236 from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors. The first author gratefully acknowledges the support of Consolidated Contractors

Company (CCC) through the CCC Doctoral Fellowship in Manufacturing.

7 REFERENCES

[1]. Mishra, R. S., and Mahoney, M. W., 2001, "Friction stir processing: A new grain refinement technique to achieve high strain rate superplasticity in commercial alloys," Superplasticity in Advanced Materials, ICSAM-2000 Materials Science Forum, 357-3, pp. 507.

[2]. Kuykendall, K., 2011, “An Evaluation of Constitutive Laws and their Ability to Predict Flow Stress over Large Variations in Temperature, Strain, and Strain Rate Characteristic of Friction Stir Welding”, PhD dissertation, Brigham Young University.

[3]. McNelly, T., S. Swaminathan, and J. Su, 2008, "Recrystallization Mechanisms during Friction Stir Welding/Processing of Aluminum Alloys". Scripta Materialia, 2008: p. 349-354.

[4]. Zhang, Z., and H. W. Zhang., 2009, "Numerical studies on controlling of process parameters in friction stir welding." Journal of materials processing technology 209.1: 241-270.

[5]. Chang, C., Lee, C., and Huang, J., 2004, Relationship Between Grain Size and Zener-Holloman Parameter During Friction Stir Processing in AZ31Mg Alloys, Scr. Mater., 51, p 509–514

[6]. Aljoaba, Sharif, et al., 2012. "Modeling the Effects of Coolant Application in Friction Stir Processing on Material Microstructure Using 3D CFD Analysis." Journal of materials engineering and performance 21.7 1141-1150.

[7]. Sellars, C. and W. Tegart, 1972, "Hot Workability". International Metallurgical Reviews, 1972: p. 1-24.

[8]. Sheppard, T. and D. Wright, 1979, "Determination of Flow Stress: Part 1 Constitutive Equation for Aluminum Alloys at Elevated Temperatures". Metals Technology, 1979: p. 215-223.

[9]. Oh, S.I., et. al., 1991, “Capabilities and applications of FEM code DEFORM the perspective of the developer”, Journal of Materials Processing Technology, 27 (199l) 25-42

[10]. EFUNDA online material library, “Magnesium Alloy ASTM AZ31B-H24 material properties”. Access date 7/5/2012.

[11]. Liu G., Zhou J., and Duszczyk J., 2008, "Process optimization diagram based on FEM simulation for extrusion of AZ31 profile", Trans. Nonferrous Met. Soc. China, 18 pp. 247-251

[12]. Buffa, G., Fratini, L., and Shivpuri, R., 2007, "CDRX Modelling in Friction Stir Welding of AA7075-T6 Aluminum Alloy: Analytical Approaches," Journal of Materials Processing Technology, 191(1-3) pp. 356-359

[13]. McQueen H. J., Myshlaev M., Sauerborn M., Mwembela A., 2000, "Flow Stress Microstructures and Modeling in Hot Extrusions of Magnesium Alloys," Magnesium Technology 2000, The Minerals, Metals and Materials Society, pp. 355-362

[14]. Nishioka, N., Chiang, L. F., Uesugi, T., Takigawa, Y., & Higashi, K., 2011, “Dynamic Friction Properties and Micro-structural Evolution in AZ 31 Magnesium Alloy at Elevated Temperature during Ring Compression Test”, Materials Transactions, 52/8:1575-1580.

[15]. Chiang, L. F., Hosokawa, H., Wang, J. Y., Uesugi, T., Takigawa, Y., & Higashi, K., 2010, “Investigation on Dynamic Friction Properties of Extruded AZ 31 Magnesium Alloy Using by Ring Upset-ting Method”. Materials transactions, 51/7:1249-1254.

[16]. Ceretti, E., Fiorentino, A., and Giardini, C., 2008, "Process Parameters Influence on Friction Coefficient in Sheet Forming Operations," International Journal of Material Forming, SUPPL. 1:1219-1222.

[17]. Nishioka, N., Chiang, L. F., Uesugi, T., Takigawa, Y., & Higashi, K., 2011, “Dynamic Friction Properties and Microstructural Evolution in AZ 31 Magnesium Alloy at Elevated Temperature during Ring Compression Test”, Materials Transactions, 52/8:1575-1580.

[18]. Ammouri, A.H., Kheireddine, A. H., Lu, T., Jawahir, I.S., Hamade, R.F., 2012, “Model-Based Optimization of Process Parameters in the Friction Stir Processing of AZ31b with Adaptive Cooling”, GCSM2012, The 10th Global Conference on Sustainable Manufacturing, Oct 31-Nov 2, 2012, Istanbul, Turkey

[19]. Kheireddine, A. H., Hamade, R.F., Ammouri, A.H., G. Kridli, 2012, “FEM Analysis of the Effects of Processing Parameters and Cooling Techniques on the Microstructure of Friction Stir Welded Joints”, IMECE2012-88943, Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition, IMECE2012, November 9-15, 2012, Houston, Texas, USA

[20]. Ulacia, I., et al., 2011, "Tensile characterization and constitutive modeling of AZ31B magnesium alloy sheet over wide range of strain rates and temperatures." Journal of Materials Processing Technology 211.5:830-839.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

12.2 Mechanical properties and surface integrity of direct recycling aluminium chips (AA6061) by hot press forging process

M.A. Lajis [1], N.K. Yusuf [1], M.Z. Noh [2], M. Ibrahim[1]

[1] Advanced Manufacturing and Materials Center (AMMC), University Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia

[2] Faculty of Science, Technology and Human Development, University Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia

Abstract

This study discusses on the effect of different chip sizes and operating temperature in recycling the AA6061 aluminum chip. It introduces a new approach of direct recycling using the hot press forging process that eliminates the two intermediate processes of cold-compact and pre-heating. The recycled specimens exhibited a remarkable potential in the strength properties where it increased with increment of total surface area of chips. On the other hand, recycled specimens with medium surface area of chips posed highest elongation to failure. Grain size and oxide amount of billet have an effect on the elongation of recycled materials. Analysis for different operating temperatures showed that the higher temperatures gave better result on mechanical properties and finer microstructure.

Keywords:

Aluminium, Hot press forging, Mechanical property, Solid-state recycling, Surface integrity

1 INTRODUCTION

Currently, with increasing waste management costs and difficulties securing final disposal landfills, the production of clean energy and the reduction of energy consumption have become the most serious sustainability issues on earth. Recently, industrial processes lead to global warming by carbon dioxide emissions and considerable amounts of solid waste, affecting human activity. Various industrial processes accounted for approximately 14% of the total CO2 emissions and 20% of the total greenhouse gas emissions in 2010 [1]. The manufacturing sector, which lies at the core of the industrial economy, must be made sustainable to preserve the high standard of living achieved by industrialised societies and to enable developing societies to achieve and maintain the same standard of living [2].

The demand for aluminium products is increasing because aluminium alloys can offer excellent corrosion resistance with high strength and low density compared with steel. Aluminium is the third most abundant element in the earth's crust after oxygen and silicon. The use of a lighter-weight material, such as aluminium, as an alternative to steel is usually considered a positive choice in terms of fuel economy. As an approximation, a 10% reduction in mass produces a 5% improvement in fuel economy [3]. Aluminium offers a numbers of benefits relative to ferrous materials, such as better ductility and malleability, better corrosion resistance, better electrical conductance, lower density and, most importantly, it is recyclable. The latter benefit will be the largest contributing factor of aluminium in industry, especially in the automotive industry. Although there are several benefits of using lighter weight materials during the life cycle of a vehicle, as the market for lightweight vehicles increases, the recovery infrastructure is likely to decrease. The existing automotive recovery infrastructure is well suited to ferrous-based vehicles. It was found that the current equipment and processes are well suited for steel-based components and a complete redesign of the equipment and processes would be needed to recover and re-manufacture the aluminium components [3]. This reason justifies the need for further research on the recovery infrastructure and recycling of automotive aluminium.

Recycling of aluminium alloy scraps and chips is usually accomplished by the melting method with a melting temperature of 660°C, making aluminium recycling an energy intensive process. Usually, the aluminium waste forms a chip from the machining of semi-finished products. Recycling of chips is difficult because of their elongated spiral shape and small size. The apparent density of the chips is low, making the chips inconvenient for handling and transportation. Their surface area is relatively large and covered with oxides and oil emulsion, which is not good for recycling by the re-melting approach [4]. The large surface area to volume ratio of the chips is also not conducive to re-melting. There are losses at every stage of the recycling process when the metal is oxidised during melting as well as some loss through mixing with the slag from the surface of the melt, and scrap results from casting and further processing of the aluminium ingots [5]. All these losses contribute to an aluminium yield that can be as low as 54% [6]. During the melting or recycling of the chips and scraps, a lot of aluminium alloy is lost from oxidation and the costs of labour and energy required for more efficient recovery [7] are prohibitive. The process was characterised by a very low metal recovery rate, high-energy consumption, and release of high levels of smoke and gases to the environment [8].

To date, several innovative processes have been proposed to recycle aluminium chips using solid-state recycling techniques. Initially, the solid-state recycling techniques used

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

powder metallurgy processes [4], followed by Fogagnolo et al. 2003 [9]. However, more recently, the solid-state technique was improved using a direct recycling method, eliminating the ball-milled process, producing fine granulated particles. Because the ball-milling step is eliminated, the process is called direct recycling. The processes used in direct recycling techniques are hot extrusion, hot rolling, etc. This process chain requires an amount of energy that is only 5-10 % of that needed for the conventional process chain that includes a re-melting step of the scrap to produce new extrusion billets [10]. The savings is because the material is recycled directly from the chips by hot press forging, resulting in a more economic process. Samuel, 2003 [5] characterised this technique by fewer steps, a higher efficiency of recovery, and lower generation of new scrap. Gronostajski et al. , 2000 [7] reported that, using this technique, 95% of metal was ultimately recovered, only 5-6 GJ of energy per ton was used, and only 2.5-6.5 man-hours per ton was required. Furthermore, Gronostajski et al., 2001 [11] found that the direct recycling technique can provide a possible reduction in the funds spent on environment protection, reduce the consumption of ores, reduce the use of energy carriers, and result in less degradation on the natural environment because of reduced air-pollution emission. Chmura and Gronostajski, 2000 [12] concluded that this technique is relatively simple, consumes a small amount of energy and does not have a harmful effect on the environment.

This study introduces a new approach of direct recycling using the hot press forging process that eliminates the two intermediate processes of cold-compact and pre-heating. This method will lead to low energy consumption and cost without intervening with the metallurgical processes. The conditions for consolidation of the chip sizes that affect the mechanical and surface integrity properties of hot forged products are rarely documented in recent literature. Oxide precipitation is closely related to recycled aluminium alloy chip size [13]. Oxidisation increases as a function of surface area, and it has been reported that oxide precipitates in the recycled specimen lead to compromised specimen ductility, especially at elevated temperatures [14]. This study investigates the effect of chip size on the mechanical properties and surface integrity of direct-recycled automotive scrap materials, using chips with model number AA6061 as secondary resources.

2 EXPERIMENTAL SET-UP AND PROCEDURES

2.1 Preparing the Chips

The AA6061 aluminium alloy chips were collected by dry milling cutting an ingot using Sodick-MC430L high-speed machining (HSM). Machined chips are kept clean with acetone after the milling process. Three machined chip samples (as shown in Figure 1) from the HSM milling, with selected machining parameters, are shown in Table 1 by the average length, width, and thickness. Chip parameters were measured by optical microscope (Olympus BX60M) in cold-mounted shape and labelled as small, medium, or large. Then, the chips were cleaned using acetone solution and dried in a furnace at 60˚C.

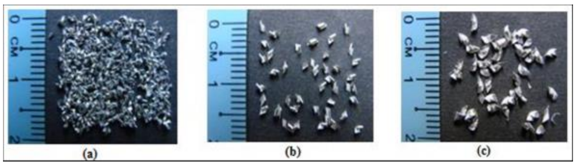


Figure 1 - Different categories of chip sizes by HSM process: (a) small-sized, (b) medium-sized, (c) large-sized AA6061 machined chips.

2.2 Recycling the Chips

Eight grams of clean chips were weighed before being poured into the mould in Figure 2(a). The selected operating temperature was 460,490,520°C at 70 MPa, by modified hot press forging, with an attached furnace as shown in Figure 2(b). The maximum operating temperature and pressure as a function of time are summarised in Figure 3. For the initial 60 minutes, the mould was heated at 8.67°C/min, before the mould reached the operating temperature, 520°C. At this stage, the pressure was two-thirds of the selected pressure, 48 MPa. The holding stage started right when the temperature reached 520°C. In 30 minutes, the heat was distributed into the entire working area. Then, the desired forging condition was met, with the pressure and temperature maintained at 70.0 MPa and 520°C. This condition was held for 120 minutes (soaking period) before cooling down to the room temperature. The recycled specimen has a dog-bone shape with the specified dimensions [15], as shown in Figure 2(c).

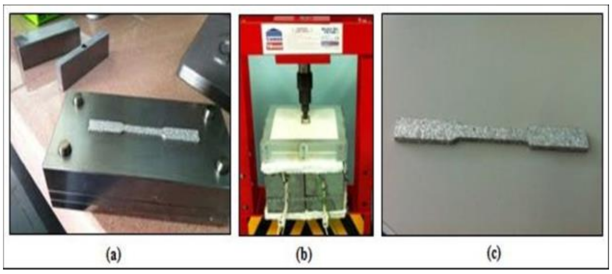


Figure 2: Hot press forging and recycled sample preparation: (a) chips filled in the mould, (b) hot press forging, (c) recycled specimen AA6061 chip.

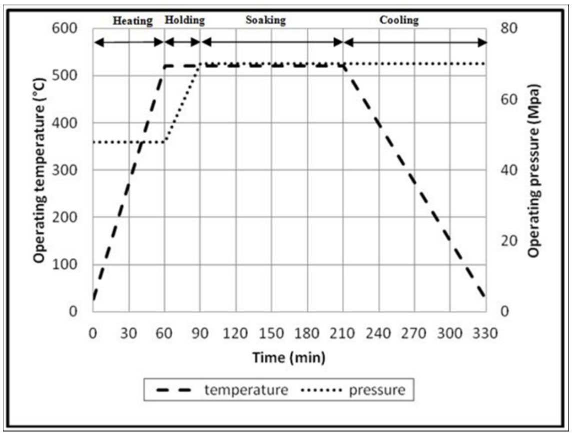


Figure 3: Hot press forging at 520^{0}C operating temperature and 70 MPa pressure as a function of time.

3 RESULTS AND DISCUSSION

3.1 Oxygen Inclusion

It is well known that some alloys are easily oxidised. Oxide film will form naturally on chip surfaces during machining and subsequent laying out. Thus, there is always some oxide in aluminum alloy fabricated from machined chips by the solid-state process. The amount of oxide is closely related to the size of the recycled-metal-alloy chips [13]. The relationship between the accumulated oxides and the total surface area of the machined chip in the recycled specimen can be estimated. If it is assumed that the shape of the machined chip is cubic, the relationship can be calculated using the following equation [16]:

$$S = 2(lw + wt + tl) / lwt \quad (1)$$

where S is the total surface area per unit volume, l is the chip length, w is the chip width, and t is the chip thickness. The oxygen content of the recycled chip is measured using an oxygen-nitrogen analyser. Table 2 summarises the calculation of total surface area per unit volume, S, with measured oxygen content for all three chip sizes. The accumulated oxygen concentration increases linearly with the total surface area. This tendency agrees well with that measured for repeatedly re-extruded metals-alloy specimens [14]. This finding indicates that the size of the machined chips is one of the important factors in the control of oxide contamination in solid-state recycling.

3.2 Microstructure

Grain size of the recycled specimens was measured using an optical microscope (Olympus BX60M) [17][18]. The specimens were polished with a Cr2O3 polishing medium and etched with Keller's reagent. Microstructures of three recycled specimens at operating temperature 520^{0}C and a reference specimen are shown in Figure 4. As illustrated in Figure 4, the average grain sizes of the recycled specimens (small, medium, and large chip sizes) are 7.90 μm, 13.45 μm, and 19.50 μm, respectively, and the reference specimen is 20.45 μm. In this study, the forging temperature for hot working is selected between the solidus temperature and the recrystallisation temperature. For AA6061 alloy designation, recrystallisation starts at 450°C, and solidus starts at 580°C [19]. The grain size of all recycled specimens, as shown in Figure 4(a-c), was smaller than the reference specimen in Figure 4(d), decreasing with increasing S value.

This can be due to the dynamic recrystallisation that occurs during the hot forming of Al-Mg aluminum alloys [20]. According to Lee et al., 2005 [21], during hot conditions, obvious distortion was produced around oxides, resulting in high dislocation density and larger orientation differences of grain boundaries in distortion areas. Distortion areas became the nuclei of dynamic recrystallisation, increasing the nucleation rate. Therefore, more oxidation will lead to higher dynamic recrystallisation, leading to a finer grain size. Furthermore, oxide suppresses grain growth during hot forming [13]. Thus, specimens with higher chip total surface area contain more oxides, and thus, specimens with a large S have a finer grain size than those with a small S.

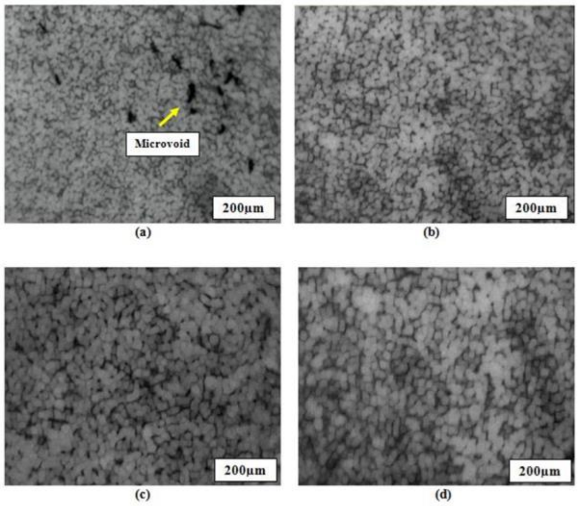


Figure 4: Microstructure of recycled specimens at 520^{0}C operating temperature: (a) small chips, (b) medium chips, (c) large chips, and (d) reference specimen of AA6061.

3.3 Mechanical Properties

Standard tensile specimens [15] were prepared to determine the two important strength values, elongation to failure (ETF) and ultimate tensile strength (UTS). The testing is performed in a universal testing machine (Shimadzu EHF-EM0100K1). Table 3 shows the UTS and ETF for three types of recycled specimens under different operating temperature of 460, 490 and 520^{0}C. As shown in Figure 5, at maximum temperature 520^{0}C, small-sized recycled specimen shows the highest UTS of 117.58 MPa, while the large-sized recycled specimen shows the lowest UTS value of 30.83 MPa. Under different operating temperature, recycled specimen with a larger S value (see Table 2) exhibits higher UTS than those with a smaller S. Compared with the strength of reference specimens, 327.69 MPa, and all recycled specimens show lower values for the UTS. For the ETF under different operating temperature in Figure 6, the medium-sized recycled specimen shows the best ductility with an 11.73% ETF at 520^{0}C operating temperature. However, the ETF for the small-sized recycled specimens and large-sized recycled specimens are much lower than that for the reference specimen (24.24%).

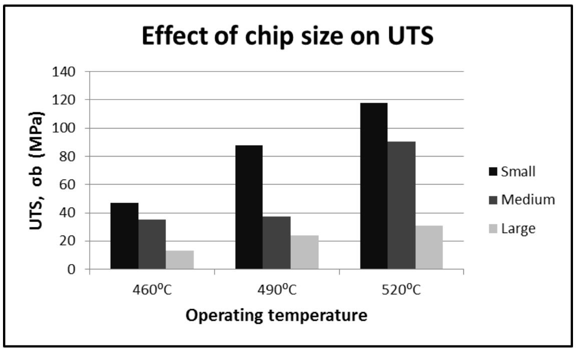


Figure 5: UTS for different chip sizes of recycled AA6061.

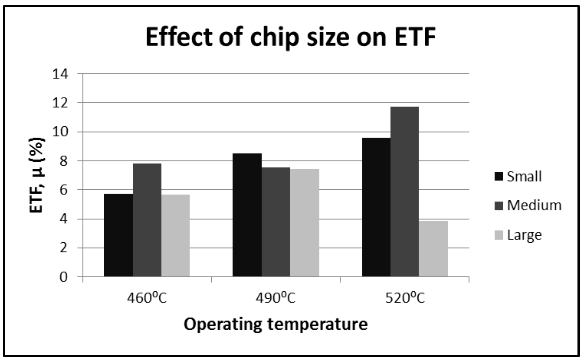


Figure 6: ETF for different chip sizes of recycled AA6061.

All physical and mechanical material properties primarily depend on the structure of the materials. The difference in grain size should be responsible for the variation of the UTS for the three recycled specimens and the reference specimen. Russel and Kok, 2005 [22] have compared the stress-strain behaviour of single crystal and polycrystalline Aluminium tensile specimens for different grain size. In general, small grain size produced close space barrier to dislocation and they show that more closely spaced barrier to dislocations will produce greater strength. On the other hand, it is known that dynamic recrystallisation occurs during hot extrusion for Al-Mg alloys. The higher strength for the small-sized recycled specimen is attributed to grain refinement strengthening and particle-dispersion [23]. The fine-grained microstructures of recycled specimens from dynamic recrystallisation during hot working lead to the higher UTS.

Although the medium-sized recycled specimen shows the highest ETF, the value of the UTS was lower than that for the small-sized specimen. The influence of chip size on the ductility of the recycled material involves several factors. In the recycled specimen with larger S, more oxides tend to form microvoids, as shown in Figure 4(a), reducing elongation. According to Chino et al., 2004 [24], cavity nucleation is stimulated by the oxides introduced from the machined chip surface, resulting in potential premature fracturing in the solid recycled specimen. In the process of tensile testing, the specimens exhibited no tendency to neck and fracture by brittle rupture. Inconsistent deformation of matrix and oxide causes stress concentration in the matrix adjacent to the oxide precipitates during tensile testing. Microvoids are prone to form in this area, which can coalesce into a large crack, resulting in potential premature fracturing [16]. Recycled specimens exhibit less elongation than the reference specimen, although grain sizes in the recycled specimens are smaller. A small amount of oxide precipitation appears to result in dispersion strengthening, but excessive oxide may cause the early development of microvoids [16].

One of the reasons the mechanical properties of the recycled specimen do not compare well with the reference specimen is due to the effect of low operating pressure (70 MPa) during the press forging process. The suggested operating pressure for AA6061 is 400-600 MPa [25]. The recycled chip still shows remarkable strengthening potential using only 17.5% of the suggested pressure (70.0/400.0) MPa. (The UTS exhibit used 35.8% (117.58/327.69) MPa.) This finding indicates that investigation of direct recycling through the hot press forging process is highly desirable for future work.

4 CONCLUSIONS

In the present study, a method of direct recycling of aluminium chip AA6061, incorporating hot press forging, is tested. Based on the tests, the following is concluded:

- The total surface area of the chips and the amount of oxide in recycled material decreases with increasing chip size. The recycled specimens with larger total chip surface area exhibit higher UTS. This is because the grain of the recycled specimen becomes finer as the chip surface area increases. The presence of oxide has a small particle-dispersion strengthening effect due to its non-homogeneous distribution, but grain refinement is also related to the presence of oxides.
- All three recycled specimens show less elongation than the reference specimen due to the presence of the oxide precipitation. The recycled material with medium chip total surface area exhibits the highest elongation due to the influence of ductility, involving the grain size and to the oxide from the recycled materials.
- Generally, it was observed that oxide in the recycled specimen contributes to higher tensile strength and ETF, whereas excessive oxide can adversely affect the ETF because a small amount of oxide precipitation appears to result in dispersion strengthening, but excessive oxide may cause the early development of microvoids and contribute to lower elongation.
- The size of machined chips is an important factor for the control of oxide contamination in solid-state recycling. It is worth mentioning that the AA6061 aluminium alloy chips in this study were recycled directly without complete melting, as in the conventional approach. The experimental materials exhibited a high potential for strength and plasticity, proving that solid-state recycling using hot press forging is an alternative method for the recycling of aluminium alloy chips. Further research is suggested.

5 ACKNOWLEDGMENTS

The authors would like to acknowledge the main support of the Ministry of Higher Education (MOHE), Malaysia, for funding this project through the Fundamental Research Grant Scheme (FRGS). Additional support was also provided by the University Tun Hussein Onn Malaysia (UTHM) for funding the student through the Grant Incentive Scheme (GIS) and proofread by Elsevier Publication.

6 REFERENCES

[1] National Research Council (NRC). Advancing the Science of Climate Change. Washington DC USA:The National Academies Press;2010.

[2] Jawahir I S, Jayal A D, Badurdeen F And Dillon Jr O W. Sustainable manufacturing: Modelling and optimization challenges at the product, process and system levels. Journal of Manufacturing Science and Technology. 2010; 2:144-152.

[3] Sutherland J W and Kumar V. Sustainability of the automotive recycling infrastructure: review of current research and identification of future challenges. Int. J. Sustainable Manufacturing. 2008;1(1/2).

[4] Gronostajski J, Kaczmar J, Marciniak H, and Matuszak A. Direct Recycling of Aluminum Chip in Extruded Products. Journal of Materials Processing Technology. 1997; 64:149-156.

[5] Samuel M. A new technique for recycling aluminium scrap. Journal of Materials Processing Technology. 2003;135(1):117−124.

[6] Lazzaro G and Atrozi C. Recycling of aluminium trimmings by conform process [C]//TMS Annual Meeting. Warrendale, PA. 1992:1230−1235.

[7] Gronostajski J, Marciniak H and Matuszak A. New Methods of Aluminum and Aluminum-alloy Chip Recycling. Journal of Materials Processing Technology. 2000;106:34-39.

[8] Puga H, Barbosa H, Soares D, Silva F, Ribeiro S. Recycling of Aluminum Swarf by Direct Incorporation in Aluminum Melts. Journal of Materials Processing Technology. 2009;209:5195-5203.

[9] Fogagnolo J B, Ruiz-Navas E M, Simon M A and Martinez M A. Recycling of aluminium alloy and aluminium matrix composite chip by pressing and hot extrusion. Journal of Materials Processing Technology. 2003;143(2):792–5.

[10] Tekkaya A E, Schikorra M, Becker D, Biermann D, Hammer N, and Pantke K.. Hot Profile extrusion of AA-6060 aluminium chip. Journal of Materials Processing Technology. 2009; 209:3343-3350.

[11] Gronostajski J, Marciniak H, Matuszak A, and Samuel M. Aluminum-ferro-chromium Composites Produced by Recycling of Chips. Journal of Materials Processing Technology. 2001;119:251-256.

[12] Chmura W and Gronostajski J. Mechanical and Tribological Properties of Aluminum-base Composites Produced by the Recycling of Chips. Journal of Materials Processing Technology. 2000;106:23-27.

[13] Shuyan W, Zesheng J, and Tielei Z. Microstructure and mechanical properties of AZ31B magnesium alloy recycled by solid-state process from different size chip. Journal of Materials Processing Technology. , 2009;209:5319–5324.

[14] Chino Y, Iwasaki H, and Mabuchi M. Tensile Properties and Blow Forming of 5083 Aluminum Alloy Recycled by Solid State Recycling. Mater. Trans. 2004;45: 2509-2515.

[15] American Society for Testing and Materials, 2003. Standard Test Methods of Tension Testing of Metallic Materials [Metric]. Annual Book or ASTM Standards, ASTM E8M. Vol. 3.01.

[16] Maoliang H, Zesheng J, Xiaoyu C, Zhenkao Z. Effect of chip size on mechanical property and microstructure of AZ91D magnesium alloy prepared by solid state recycling. Journal of Material Characterization . 2008; 59:385– 389.

[17] American Society for Testing and Materials, 2001. Standard Guide for Preparation of Metallographic Specimens, ASTM International, West Conshohocken, PA, ASTM E3–01.

[18] American Society for Testing and Materials, 2006. Standard Test Method for Macroetching Metals and Alloys, ASTM International, West Conshohocken, PA, ASTM E340.

[19] Metals Handbooks, Desk Edition. ASM 1998. ISBN 0-87170-654-7

[20] Sheppard T, Parson N C, and Zaidi M A. The Extrusion of Atomised Aluminum Alloy Compacts and Composites. Journal of Mechanical Working Technology. 1983;8(1):43-70.

[21] Lee J S, Chino Y, Hosokawa H, Shimojima K, Yamada Y, and Mabuchi M. Deformation Characteristic at Elevated Temperature in Recycled 5083 Aluminum Alloy by Solid State Recycling. Mater. Trans. 2005;46: 2637-2640.

[22] Russel, M. A. and Kok, L. L. Structure-property relations in nonferrous metals. New Jersey: Wiley Intersciene; 2005.

[23] Chino Y, Otsuka S, Mabuchi M , Shimojima K., Hosokawa H, Yamada Y, Wen C, and Iwasaki H. Corrosion and Mechanical Properties of Recycled 5083 Aluminum Alloy by Solid State Recycling. Mater. Trans.2003; 44:1284-1289.

[24] Chino Y, Lee J S, Nakaura Y, Ohori K and Mabuchi M. Mechanical properties of Mg–Al–Ca alloy recycled by solid-state recycling. Mater. Trans. 2005; 46: 2592–2595.

[25] Kurt Lange. Handbook of metal forming. University of Stuttgart: McGraw-Hill Book Company; 1985.

Table 1 : HSM and chip AA6061 parameters.

HSM PARAMETER				CHIP PARAMETER (MM)		
Type	Cutting Speed, v (m/min)	Feed, f (mm/tooth)	Depth of Cut, DOC (mm)	Average Length (l)	Average Width (w)	Average Thickness (t)
Small	1100	0.02	0.5	6.10	0.535	0.021
Medium	1100	0.05	1.0	5.20	1.097	0.091
Large	1100	0.10	1.5	4.30	1.535	0.145

Table 2: Results of the oxygen amount.

SIZE	SIZE PARAMETER OF CHIP (mm)			SURFACE AREA PER UNIT VOLUME, S (mm²/mm³)	OXYGEN AMOUNT, PART PER MILLION (ppm)
	Length, l	*Width, w*	*Thickness, t*		
Small	6.10	0.535	0.021	99.30	21.67
Medium	5.20	1.097	0.091	24.19	5.43
Large	4.30	1.535	0.145	15.56	2.13

Table 3: Results of UTS and ETF for three types of recycled specimen.

NO	TYPE	OPERATING TEMPERATURE (°C)	OPERATING PRESSURE (MPA)	ULTIMATE TENSILE STRENGTH, UTS (MPA)	ELONGATION TO FAILURE, ETF(%)
1.	Small	460	70.0	47.14	5.6
2.	Small	490	70.0	87.30	8.19
3.	Small	520	70.0	117.85	9.5
4.	Medium	460	70.0	35.18	7.71
5.	Medium	490	70.0	37.165	7.62
6.	Medium	520	70.0	90.431	11.84
7.	Large	460	70.0	13.41	5.78
8.	Large	490	70.0	23.81	7.15
9.	Large	520	70.0	30.73	3.84

12.3 Ecological evaluation of PVD and CVD coating systems in metal cutting processes

F. Klocke [1], B. Döbbeler [1], M. Binder [1], N. Kramer [2], R. Grüter [2], D. Lung[1]

[1] Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Germany
[2] KOMET Group GmbH, Besigheim, Germany

Abstract

Due to the ongoing demand for sustainability assessments regarding manufacturing processes, this paper concentrates on the factor of coated cemented carbide tools. Previous publications have shown the potential ecological benefit of coated vs. uncoated tools. In this paper data which has been gathered from the KOMET group providing PVD- and CVD-coatings as well as sound assumptions for the assessment of coatings for cemented carbide tools, especially for indexable inserts, will be presented. Furthermore, the performed ecological assessment and its respective results will be shown. These results can be used for further and broader studies regarding the impact of cutting tools within manufacturing. Finally, the use of coatings for cemented carbide tools and their advantageousness will be discussed.

Keywords:
Ecological evaluation, Sustainability, Manufacturing

1 INTRODUCTION

The scarcity of resources, not only energy resources such as oil or natural gas, but also noble earths and metals like zinc and copper stands in sharp contrast to the tremendously rising demand for goods and services due to growing world population and the striving for a higher living standard in emerging economies. In order to meet the challenges which accrue from this fact, more transparency concerning energy and material consumption is required. Furthermore, the outlined development causes severe environmental concerns. Phenomena like the global warming are very complex and the impacts of processes are hard to quantify.

The Life Cycle Assessment methodology is a widespread procedure to both foster the understanding and transparency of material and energy streams and to generate resilient conclusions about the ecological performance. Whereas Life Cycle Assessments in the narrow sense cover the entire Life Cycle of a product embracing raw materials production, manufacturing, use and recycling or disposal, the assessments in the area of production often focus on the phase of manufacturing [1][2]. The perspective is also called the cradle-to-gate point of view which takes raw materials exploitation, processing and manufacturing into account. The results of cradle-to-gate investigations can be combined with results obtained for the use and disposal phases in order to achieve a holistic Life Cycle Assessment.

The manufacturing sector is the backbone of modern economies. As such it allows for employment, prosperity and innovation. A contribution of the manufacturing sector is indispensable for a sustainable development, since much energy and resources are spent for production directly and indirectly. Furthermore, the energy and material consumptions of many products, such as gas turbines or combustions engines, are extensively affected by the manufacturing phase. Therefore, manufacturing is a key sector to enable a sustainable development. [3]

Aware of their responsibility, many companies define and communicate targets for them selves regarding environmental issues. The reduction of equivalent carbon dioxide emissions for instance is a prevalent goal for companies. Therefore, it is necessary to assess industrial production to obtain the ability of comparing the goals with the achieved progress. Furthermore, environmental issues increasingly gain importance for marketing reasons. Customers ascribe a rising importance to the sustainability of products. Some automotive companies even commit their suppliers to provide information about environmental issues such as the carbon footprint [4][5].

The metal working industry is affected by this development. Since the EU 2009 explicitly identified the machine tool as a energy using product [6] with a high improvement potential concerning energy efficiency, many initiatives [7] and scientific projects [8] dealt with the machine tool hardware and software and aimed at a higher efficiency. Besides, the processes have been analysed and balanced [9][10]. It has been shown, that in metal cutting, the energy and resource consumption per manufactured part is highly dependent on the chosen set of machining parameters. If the use of cutting tools is neglected, the efficiency of the metal cutting process rises with higher cutting parameters. This is due to two reasons. Firstly, the metal cutting itself becomes more efficient [9][10]. Secondly, the base load of the machine tool which is caused by hydraulics, ventilation or coolant pumps for instance can be attributed to a higher output and thus the efficiency rises. Because the use of the cutting tools needs to be taken into account for a holistic analysis, the production of the cutting tools including an optional coating needs to be assessed. The increase in cutting parameters under consideration of the efforts for tool production leads to opposing trends. Whereas the process itself is more efficient, the expenditure of cutting tools is higher. An optimum in the process design can only be determined if the cutting tools are thoroughly balanced and assessed.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2 COATINGS IN METAL CUTTING PROCESSES

In this chapter of this paper, the basic properties of CVD and PVD processes in general and the investigated processes in detail have to be elaborated in order to evaluate the results later on.

Coatings in metal cutting processes are supposed to increase the productivity due to higher cutting parameters as well as the wear resistance of the tools. Since most of the cutting tools nowadays are coated, the importance of the underlying process and the necessary environmental impact has grown significantly. Coatings are used to decrease the effects of the causes for wear development, namely abrasion, adhesion, oxidation and diffusion [11].

On the one hand, coatings prohibit the mechanisms of adhesion, oxidation and diffusion due to their surface properties and act as a barrier between the workpiece and the tool material. The coating itself has to be worn off in order for the tool substrate to be affected. On the other hand, the coating material itself usually features high hardness and thermal stability and thus is able to withstand the mechanical and thermal loads of cutting processes in an enhanced manner. By using coatings, the cutting parameters and therefore the productivity often can be increased [11]. Furthermore the coatings need to be selected carefully, since different work piece materials require different coating systems in order to increase productivity or process stability.

Additionally to these basic properties of coatings, it is necessary to emphasize that the coating process itself should not reduce the inner bonding strength, e.g. the toughness of the substrate, whilst applying the necessary tool wear development inhibition features. For coating cemented carbide tools several processes are available which can be divided into physical vapour (PVD) and chemical vapour deposition (CVD). A short overview about both process designs is necessary for the underlying investigations. CVD processes take advantage of chemical reactions in a gaseous phase under vacuum conditions (10^3-10^5 Pa). With help of thermal energy hard materials such as TiC and TiN can be formed and chemically applied to the substrate material. This chemical reactions highly rely on the partial pressure of the gaseous components and the temperature of the process [11]. In the investigated process gases such as hydrogen (H_2), nitrogen (N_2), methan (CH_4), carbon monoxide and carbon dioxide (CO, CO_2), titaniumtetrachlorid ($TiCl_4$) as well as acetonitrile (CH_3CN) were measured, see Figure 1.

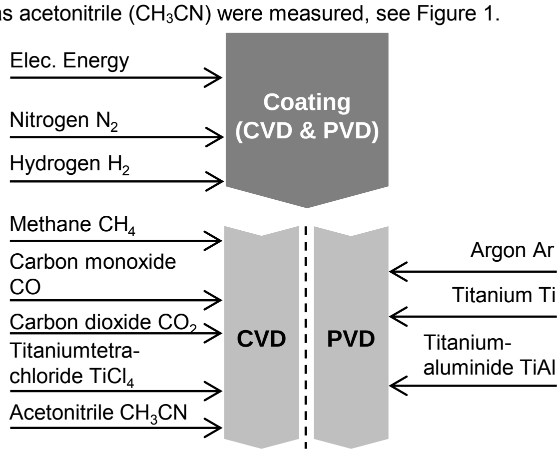


Figure 1: Measured data in the CVD and PVD process

Furthermore, the necessary electrical energy has been acquired during the process time. The investigated coating is TiCN-TiN-Al_2O_3. The small amount of Al_2O_3 could not be measured and therefore is neglected.

Both process designs can further be sectioned into different process principles. Within this paper a sputter PVD as well as a high temperature CVD process, which are common for applying coatings for metal cutting, are highlighted and investigated.

PVD sputter processes are fueled by an inert gas, often argon, which is ionized by applying high voltage in a low pressure plasma. This positive inert gas is accelerated on the target switched as a cathode and thereby knocks out atoms, molecules of the coating material via impulse exchange. This target material then applies on the substrate material on the one hand because of the high speed as well as due to a condensation process on the other hand. Beside the electrical energy, during the investigations argon (Ar), nitrogen (N_2) and hydrogen (H_2) gas have been measured in order to provide solid data for the whole process. The applied coating is TiAlN/TiN. Both results can be seen in the results part.

CVD and PVD coating principles lead to different properties of the cutting tool coatings. In a sputter PVD processes the bonding power of substrate and coating is not as high as in CVD processes. CVD processes on the other hand have the big advantage of being able to coat complex geometries due to the gaseous chemical reaction. PVD processes have a direction-based principle, which leads to the necessity to turn all tools during the process in order to assure a evenly distributed coating. One very important difference is the generation of residual stresses in the substrate and coating. Whereas by a PVD process usually residual compressive stress can be observed, CVD processes often induce residual tensile stresses. For the application in cutting processes, the compressive stresses prohibit crack initiation and further crack development and are therefore more valuable in many situations. Also the PVD principle, specially the sputter process, does not require very high temperatures, such as the high-temperature CVD process. This is beneficial when coating high speed steel (HSS) substrate materials, because by typical HT-CVD temperatures the material itself will be altered with respect to the material structure similar to a heat treatment process [11].

Furthermore the different principles for applying coating materials offer various possibilities with respect to coating thicknesses and coating materials. For the most common materials such as TiN, TiC, Al_2O_3 both principles are possible. Diamond-like-carbon coatings and diamond coatings itself are applied using CVD-techniques. [11]

In the following Figure 2, the typical process chain of cemented carbide cutting tools, including the coating processes, is shown. Usually the metal powder is prepared and sintered. Furthermore, additional processes such as grinding for complex geometries, i.e. for chip breakage, or the application of coating are possible finishing operations. In order to provide valuable data several variations have been investigated.

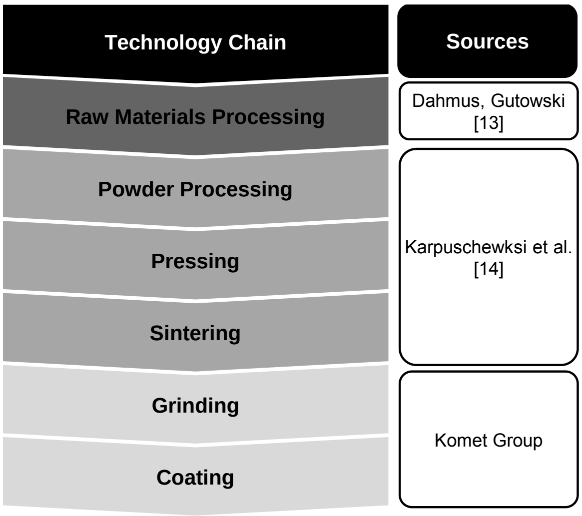


Figure 2: Underlying technology chain for the indexable inserts

The additional grinding processes as well as the coating process are not performed for every tool. In the investigations the whole process chain has been evaluated in order to estimate the relation of coating processes to the whole efforts for the finished cutting tool.

For the final application in industrial cutting processes, the information how high the impact of applying coatings and finishing grinding operations actually is, can change the ecological advantageousness. As already mentioned, the application of coatings may allow higher cutting parameters. These higher parameters usually lead to a reduced energy consumption per volume during the process due to the reduction of process times. Furthermore, this reduction leads to less consumption of the non-process related components of machine tools such as hydraulic systems, lubricoolant pumps and the control unit, which often are responsible for the major share of the total power consumption. Still, high performance cutting processes, in which the major share of the power consumption can be lead back to the process forces, may not show reduced energy consumptions due to the working point of the spindle motor or machine tool components. From a theoretical point of view higher cutting parameters such as increased cutting speed or feed, lead to lower process consumptions. The cutting forces increase degressively whereas the material removal rate increases linearly. Previous works already focused on the influence of the different cutting parameters and the effect of the component related consumptions [9][10]. It can be stated that the application of coatings often leads to energy consumption reductions per part due to shorter process times. On the contrary, additional efforts have to be invested into the application of the coatings, which are the main focus of this paper.

3 METHODOLOGY

The evaluation procedure is based on the LCA methodology in accordance with DIN EN ISO 14040/14044 [1][2]. This widely accepted systematic approach offers a framework to assess the ecological performance of a product. The approach is divided into four steps, as visualized in Figure 3.

In a first step, the appropriate definition of the balance shell is set and a functional unit is specified. The results of a LCA are always related to a functional unit as it is a relative approach. The functional unit can be a product, i.e. a tool or a coating, or more abstract the transportation of a ton of goods over one kilometer. The functional unit is a quantitative measure of the functions that the good or the service provides [12]. In addition to the balance shell and the functional unit, the impact categories of interest have to be named. The impact category specifies the environmental category of concern such as climate change or the scarcity of resources. Finally, the goal of conducting the study is of crucial importance to the the entire investigation as it determines the specification for the study.

Subsequently, the energy and material flows within the specified balance shell are determined and quantified. The data acquisition within this second step of inventory analysis can be based on different strategies. The material and energy flows can be measured, calculated, estimated or provided by data available in accountancy. Both, effort and quality of the executed LCA dramatically depend on the data acquisition. Therefore, the data acquisition needs to be performed as detailed as necessary to meet the goals set in the first step. Nevertheless, as the data acquisition is a major effort in the entire approach, it should not be performed as detailed as possible.

The result of the inventory analysis is a input/output-balance of the investigated process, which is not yet assessed. It covers different material or energy streams that cannot be directly compared, as they are measured in different units. Thus, in a third step, the inventory data is assessed. During the assessment, the environmental significance of a certain flow against the background of an impact category or several categories is evaluated. Thus, the perspective changes from a exclusively quantitative to a qualitative perspective. Impact categories are a set of scientifically elaborated factors. They quantify the theoretical impact of every material and energy flow gathered within the inventory analysis. The most discussed impact category for example is the Global Warming Potential which, is measured in kg CO_2-Equivalents. For the assessment of the energy and material flows, the use of Life Cycle Inventory Databases is widespread. These databases contain sets of factors that can be used to assess common energy and material flows against the background of common impact categories.

In a fourth step, the generated results are critically questioned, checked for consistency and carefully interpreted due to the fact that the results of a LCA need to be considered as potential effects, not actual effects. Although the LCA follows the described four-step procedure, it’s progress should be understood as iterative. As the steps are interdependent, a critical reflection of the results may lead to an adaption of the chosen balance shell or assumptions made and thus may lead to another iteration through the four steps.

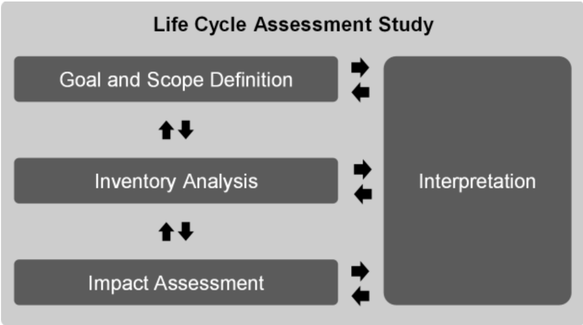


Figure 3: Framework of LCA according to DIN EN ISO

The case study of this paper bases on the described procedure. The goal of the study was to identify the energies and materials that are expended for the coating of tools for metal cutting. The motivation of KOMET was to investigate the environmental performance of their products and to proactively give customers information about performance indicators, such as the carbon footprint of their products. In order to meet that goal, a cradle-to-gate analysis was performed on a set of products, in a first step. These products cover coated and uncoated indexable inserts, solid carbide twist drills, drills for indexable inserts, replaceable drilling and drilling heads and a standard tool holder and thus, a representative set of products. In this paper the focus lays on insert cutting tools of two different sizes (small: 5 mm, big: 12 mm).

For the balance shell the cradle-to-gate approach was selected and thus the raw material production was accounted for by using data from the literature [13][14]. The energy and material flows for the process chain were quantified by both measurements and estimations combined with data obtained by the ERP system. The measured processes include the cutting tool grinding and coating, which is performed at the company. In order to provide holistic data, the infrastructural consumptions, such as lighting, heating and pressurized air, have been accounted to the single processes. Yearly calculations and the total machine hours have been used to determine key consumption indicators per machine hour. In this scenario only the consumptions of the production areas have been considered. With this approach the carbon footprint of cutting tools can be provided. Nevertheless, the infrastructural efforts have been neglected for this paper, in order to compare the processes on a technological level.

The environmental data for different materials has been gathered from the life cycle assessment software Gabi 5 [15]. In order to provide reliable results the assumptions during material attribution has to be elaborated. For H_2, N_2, CH_4, CO, CO_2, Ar and Ti values were taken from the software database. Since raw titanium usually can be gathered from $TiCl_4$ as an intermediate product, titanium values were used as a estimation to the safe side. This investigation lacks clear data for H_2S, therefore these small consumptions are neglected. CH_3CN is a joint product of the acrylonitrile production. Therefore this material with a factor of 50 % has been used.

4 RESULTS

As stated in the methodology approach of this paper, the results can be divided into different sections. Firstly, the comparison of the different coating procedures is obvious. In this case, the high temperature and middle temperature CVD vs. the sputter PVD. Secondly, the influence of the grinding and coating process after the sintering of the metal powder will be highlighted in order to estimate the relations of necessary consumptions during the manufacturing of the substrate, complex geometries and the coatings. This also leads to the cradle-to-gate balance shell, which includes all processes of the technology chain of the cutting tool manufacturing excluding the industrial application in cutting processes.

In Figure 4 both coating technologies for the two different cutting inserts are compared. The figure envisions the shares of primary energy demand for different processes, the material, grinding and coating (electrical and gases). The scale of the diagrams are different as the production of the bigger insert requires more than 10 times the primary energy demand of the small insert due to the higher volume and thus higher efforts for the substrate material itself. Also the CVD coated big insert is slightly bigger (13,2 instead of 12 mm) than the PVD-coated insert, which accounts for the higher material energy demand shown below.

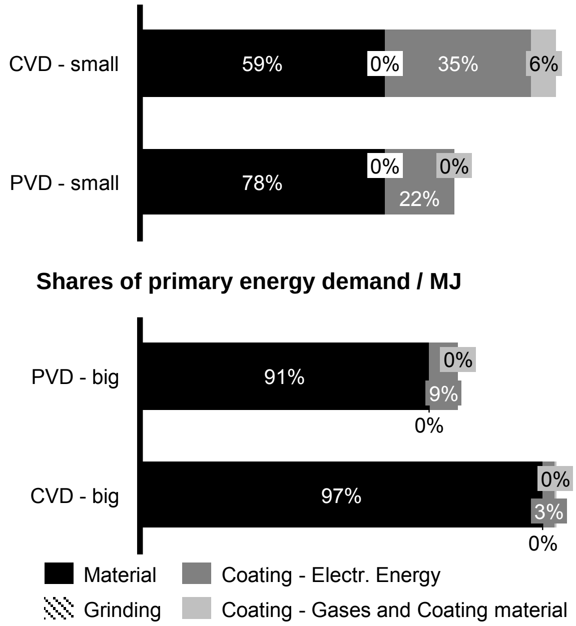


Figure 4: PVD vs. CVD coating process (small and big insert)

The figure above shows that the investigated PVD coating process usually demands less electrical energy as well as efforts for the gases during the process. Especially for the smaller tools this finding can be observed as the impact of the substrate material is not as dominant as in the manufacturing of the big insert. Furthermore, the results show that the influence of the process gases is mostly neglectable, especially for the PVD process. During the high temperature CVD process hydrogen and titanium tetrachloride have the most significant impact by far. Still it only contributes a small share to the total consumption of primary energy of the investigated coating processes.

The second result diagram can be found in Figure 5. It also envisions the shares of primary energy demand. In this case the PVD-coated 12 mm cutting insert from the previous figure is compared to inserts, which a grinded after sintering. This leads to much higher demands of primary energy. Grinding of tools it not always necessary. Data from KOMET Group states that around 30 % of the inserts have to be ground and therefore require the additional effort shown below.

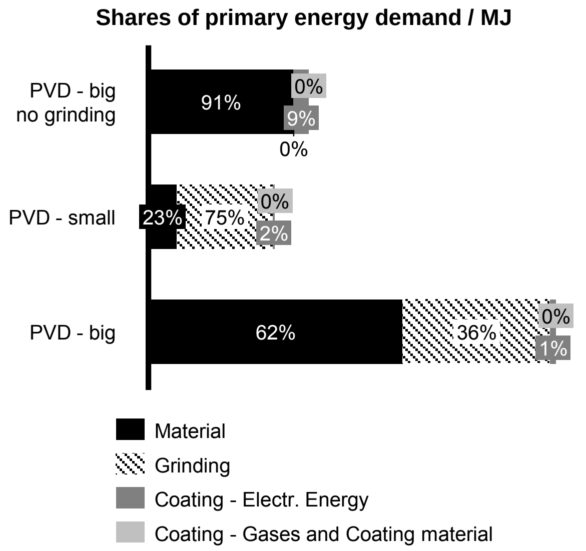


Figure 5: Geometry grinding vs. no finishing process

The small PVD-coated cutting insert, which needs to be ground after the sintering process due to required complex geometries such as chip breakers or cutting edge roundings, demands almost as much primary energy as the big PVD-coated insert without any grinding process. When highlighting the big tool with complex geometry requirements, thus necessary efforts due to grinding, the increased primary energy demand is even more significant. The demand of the big and ground PVD-coated insert is more than doubled in comparison to both inserts (small PVD-coated and ground, small PVD-coated) shown in the figure above.

Basically, the share of the coating process decreases with the increasing size of the cutting insert due to the material and grinding efforts. This is easily explained by the process principle, which allows to coat several thousand parts in one process. Nevertheless, the grinding process can only handle a few work pieces at a time on a machine tool.

5 CONCLUSION

As shown in the results part of this paper, the ecological impact of manufacturing cutting tools highly depends on the final geometry complexity, the size of the tools and the coating. Whereas manufacturing efforts of small CVD-coated tools may be influenced by the coating process in relation to the total manufacturing demands due to the small weight, manufacturing efforts for bigger tools (12 mm) are not significantly influenced by the coating process. This can change for very big and complex tools, since less numbers of tools can be coated simultaneously. Furthermore, the PVD process, which is less consuming in respect to gases and electrical energy compared to the CVD-process, cannot be used for any desired geometry due to the directional principle of applying the coating material and thus the necessity to turn the work pieces. Therefore higher consumptions have to be tolerated, if only CVD-coatings can achieve the necessary properties.

The shown results indicate that for a broad bandwidth of cutting inserts without complex geometries the accounting of the material is of utmost importance and leads to valuable results, which can be used for the carbon footprinting. With respect to complex geometries the machine tools necessary should be included into the investigations, because of their significant impact on the total manufacturing efforts of cutting inserts.

As shown in previous works, the advantageousness of coatings for cutting tools depends on the productivity and tool life time benefits provided by the coating [16]. As the results show, already small benefits may lead to the desired increased material and energy efficiency. Coating efforts do not account for more than 10 % of the total manufacturing efforts of the tools in this investigation, except for very small tools. Savings can mainly be achieved by using less tools, thus less primary energy demand.

It might be interesting to investigate very big and complex cutting tools in order to determine the impact of the material and the processes under more extreme conditions.

The investigations of this paper lead to further research areas, as the real connection between the necessary ecological impact during manufacturing cutting tools and the application including the tool life time and process parameters has not been finally established. Further investigations may lead to empirical decision supporting models and methodologies, which enable especially small and medium-sized enterprises to choose suitable cutting tools from an economic and ecological point of view.

6 ACKNOWLEDGMENTS

The authors of this paper would like to kindly acknowledge the support and data supply performed by the KOMET Group GmbH.

7 REFERENCES

[1] DIN EN ISO 14040 (November 2009). Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen.

[2] DIN EN ISO 14044 (Oktober 2006) Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen

[3] Brühl, J.; Döbbeler, B.; C. Essig C. Hein C. Herrmann P. Jahns M. Kleinjans F. Klocke D. Lung R. Schlosser A. Werner: Nachhaltige Produktion. In: Brecher, C.; Klocke, F.; Schuh, G.; Schmitt, R. (Hrsg.): Tagungsband Aachener Werkzeugmaschinenkolloquium 2011. Aachen. Aachen: Shaker, 2011, S. 196–227.

[4] BMW Group: BMW Group International terms and conditions of purchase for production material, 2010.

[5] DAIMLER AG: Daimler Nachhaltigkeitsbericht 2011, 2012.

[6] European Comission (2009). Guideline 2009/125/EG

[7] N.N. (2011): Zukunft im Blick – Nachhaltigkeit und Effizienz in der Produktion (Blue Competene, VDW)

[8] Brecher, C.; Triebs, J.; Heyers, C.; Jasper, D. (2012): Effizienzsteigerung von Werkzeugmaschinen durch Optimierung der Technologien zum Komponentenbetrieb –EWOTeK. Apprimus Verlag,, ISBN 978-3-86359-088-8

[9] Schlosser, Ralf; Klocke, Fritz; Lung, Dieter (2010): Energy and Resource Consumption of Cutting Processes. How Process Parameter Variations can Optimise the Total Process Efficiency. In: CIRP (Hg.): 17th CIRP International Conference on Life Cycle Engineering (LCE 2010). 19.05-21.05, Anhui, China, 19.05-21.05.

[10] Schlosser, Ralf; Klocke, Fritz; Lung, Dieter (2010): Sustainability in Manufacturing. Energy Consumption of Cutting Processes. In: Günther Seliger und N. Khraisheh M. K. Ibrahim (Hg.): Proceedings on the 8th GCSM conference. GCSM 2010, Abu Dhabi, 22.-24.11.2010.

[11] Klocke, Fritz (2011): Manufacturing Processes. Berlin, Heidelberg, New York: Springer (RWTH edition).

[12] Finnveden, G.; Hauschild, M.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S., 2009, Recent developments in Life Cycle Assessment, in Journal of Environmental Management, S. 1-21.

[13] Dahmus, J.; Gutowski, T. (2004): An Environmental Analysis of Machining. Proceedings of IMECE2004. S.1-10

[14] Karpuschewski, B.; Kalhöfer, E.; Joswig, D.; Rief, M. (2011): Energiebedarf bei der Herstellung von Hartmetallwendeschneidplatten. In ZWF 09, S. 602-605

[15] GaBi 4 / GaBi 5: Software und Datenbank zur Ganzheitlichen Bilanzierung. IKP, Universität Stuttgart und PE International AG, Leinfelden-Echterdingen, 1999-2011. www.gabi-software.com.

[16] Klocke, Fritz; Döbbeler, Benjamin; Binder, Marvin; Schlosser, Ralf; Lung, Dieter (2013): Ecological Assessment of Coated Cemented Carbide Tools and their Behavior during Machining. In: Re-engineering Manufacturing for Sustainability. Proceedings of the 20th Cirp International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013: Springer Verlag.

12.4 Resource-saving manufacturing of more dimensional stiffened sheet metals with high surface quality and innovative lightweight products

F. Mirtsch [1], M. Mirtsch [1], S. Lewkowicz [1]

[1] Dr. Mirtsch Wölbstrukturierung GmbH, Berlin, Germany

Abstract

Vault-structured sheet metals are produced in a unique material and surface preserving way. Hexagonal structures evolve instantly and energy-minimized with lowest strain hardening when a curved material is partially supported and loaded with very low external pressure. Synergetic properties are a reduced weight by increased rigidity, reduced droning of vibrating components, increased thermal stability by avoiding wrinkling (e.g. by welding heat), enhanced crash-energy absorption, large reserves for secondary forming, and preserving of initial surface qualities. Structure conform secondary forming techniques are invented and realized such as a bending technique with additional enhanced rigidity and fine structures for joining with quasi planar edges.

Exemplary vault-structured light weight products are an automotive catalyst cylinder made of stainless steel (Emitec), aluminium back-panel (Daimler SLK), demonstrator of a vault-structured perforated sheet metal which is deep drawn to a 3D-shape (Graepel), coiler plate "CLEANcoil" for spinnery machines (Rieter), Miele washing drum and a vault-structured façade (Manhattan, USA) made of perforated stainless sheet metal.

Keywords:

Energy-minimization; Hexagonal structures; Lightweight products; Self-organization; Vault-Structuring

1 INTRODUCTION

In addition to reduced weight, innovative lightweight components often need to fulfil further requirements such as surface quality, acoustic properties and high crash energy absorption. Preferably these products should be manufactured with improved resource efficiency.

The stiffening of sheet materials is usually accomplished by conventional forming operations such as rolling, embossing, and hydroforming (Figure 1).

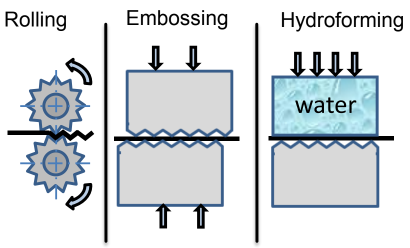


Figure 1: Conventional forming operations for production of stiffened secondary design elements (e.g. structures)

These conventional forming techniques can result in several disadvantages:

- The material is highly plasticized and partially thinned.
- A large work hardening of the material allows only low deformation degrees for secondary forming as well as low crash energy absorption.
- Large forces during forming operation lead to significant energy consumption.
- The surface quality is often affected by tool contact.

One approach in the design of sustainable products is to transfer evolutional principles of nature into technical applications. The comparison of the traditional technical way (Figure 2, top) of producing products with the biological way (Figure 2, bottom) for producing similar products demonstrates the potential of learning from nature.

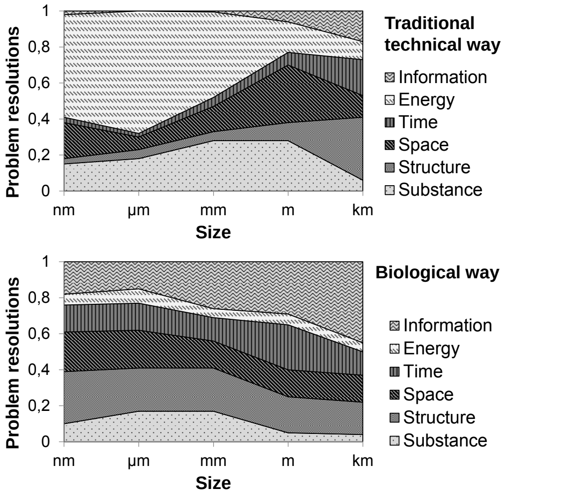


Figure 2: Problem resolutions (e.g. resources) according to size (product) by traditional technique and biological way [1]

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

Following question can be asked: “How is it possible that processing learnt by nature is usually much more sustainable and beneficially utilized than traditional technical processing?” As shown in figure 2 for products generated by the biological way the substance is reduced approximately to 50% and at least only 1/10 – 1/20 of the energy consumption is needed. Here the “Structure” and the “Information” which can be interpreted as the intelligence to generate the structures play a significant role.

That is a great stimulation and challenge for technical processes to learn from the biological way. Nature reveals that it is possible to generate highly stiffened structures with little plastic deformation of the material without tool dependent forming operations. Thereby the principles of self-organization and energy minimization play a decisive role. Paul Green [2] has shown in his fundamental work that stiffening macrostructures such as plant or animal shells can be traced back to physical principles of self-deformation of thin plates or shells (Karman equations). During growth of plant or animal shells compressive stresses are built up in membrane direction which leads to instabilities. By overcoming these instabilities new stiffening structures evolve ("buckling propagation" [2]). In industrial technology, usually no growing materials are available. The Dr. Mirtsch Wölbstrukturierung GmbH has traced a different path to generate compressive membrane stresses with resulting stiffening structures: a partially supported, curved sheet material buckles to staggered structures when a moderate external pressure is applied. Thus, a multidimensional stiffening of thin materials of different kinds can be achieved. The buckling process with a commonly negative interpretation receives here a different significance.

2 VAULT - STRUCTURING TECHNIQUE

2.1 Basic process and further development of the Vault – Structuring Technique

The basic process of vault-structuring is based on a self-organized buckling phenomenon (Figure 3) of a pre-curved, thin-walled material [3]: A supporting spiral serves as a "tool". A thin-walled cylinder is put over the spiral so that the spiral is in contact with the inner face of the cylinder. By applying a comparable low external pressure quadrangular staggered structures evolve spontaneously and energy minimized. The approximately horizontal structure folds are generated by forming against the supporting spiral. The vertical folds however evolve by themselves without an underlying tool contact.

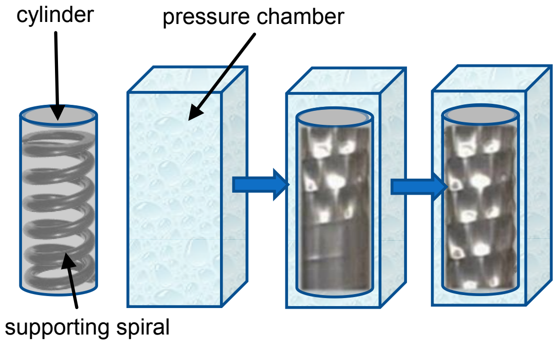


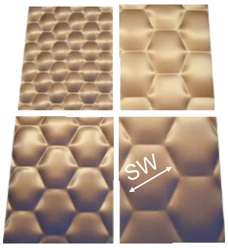
Figure 3 : Basic Vault-Structuring process with rectangular structures

This forming process is particularly gentle on the material because the resulting structure depth is mainly generated by dominant compressive membrane stresses with additional moderate bending stresses. In that way material thinning doesn’t occur. Additionally the energy consumption to generate the structures is drastically reduced compared to conventional forming (e.g. embossing) of structures.

A rectangular structured cylinder shows after straightening to a planar sheet one significant disadvantage: In the direction of the previously horizontal folds the bending stiffness is increased; in the transverse direction however the bending stiffness is low (similar to corrugated card board).

Using a supporting spring, which is not rigid but slightly flexible, a more complex self-organized structure formation occurs: At first (at very low pressure) the self-organized forming process is initiated. Afterwards the approximately horizontal structure folds develop by themselves to “zig-zag” shaped structure folds, resulting in the hexagonal vault-structures of the Dr. Mirtsch Wölbstrukturierung GmbH. Simulations of Prof. Böhm (Institute of Mechanics, Technical University of Berlin), indicated that compressive membrane forces spread out from the structure folds in the direction of the structure moulds. In this way the material obtains gentle force flows both during the structuring process itself as well as during the utilization phase of the component. These hexagonal vault-structures result in a more uniform bending stiffness in different directions than the rectangular structures.

The vault-structuring process of thin walled cylinders is limited to few applications, because large sheet panels and coils are often required. Additionally, slightly irregular structures caused by material inhomogeneities can occur when the basic vault-structuring process is applied. Therefore research and technical implementations were carried out to invent and realize a semi-continuous or continuous vault-structuring process to produce sheet panels and coils with exactly uniform structure geometry (contour of the hexagonal structure in top view). The process of structure formation is here assisted by partially acting, corrective supporting elements. Standard vault-structures for sheet metals or coils with different structures widths (SW = wrench size of the hexagon) of Dr. Mirtsch Wölbstrukturierung GmbH are shown in Figure 4.



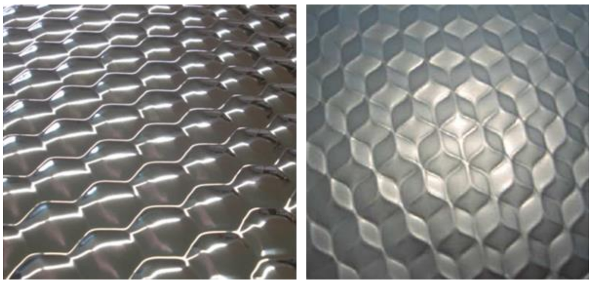
Standard Structure Width (SW):
SW 17; SW 33; SW 40; SW 50

Maximum wall thickness:
Steel: up to 1,0 mm
Aluminium: up to 1,2 mm

Maximum Dimensions:
Plate: 4.000 x 1.200 mm (l x w)
Coil width: up to 1200 mm

Figure 4: Standard vault-structures of Dr. Mirtsch Wölbstrukturierung GmbH

As further developments of vault-structures Dr. Mirtsch Wölbstruktureierung GmbH invented the structure types WaveHex® and MiCubix® (Figure 5).



WaveHex® MiCubix®

Figure 5 : Vault-Structures WaveHex® and MiCubix®

WaveHex® is characterized by particular smooth curves in the structure folds (waveform). Thus, the local plasticization in the structure folds is further reduced. The spatial facet structure MiCubix® is – compared to the hexagonal vault-structure – arranged with three additional folds for every single structure. The result is an optical appearance of regularly arranged 3D-cubes. The bending rigidity is more homogeneous in different directions compared to the hexagonal vault-structures.

2.2 Material spectrum of vault-structures

Vault-structures are applicable to a wide range of materials (Figure 6).

Metals Polymers/ Fibre reinforced plastic Paper/Cardboard

Figure 6 : Spectrum of vault-structured materials

Vault-structures can be applied on all thin walled metals such as steel, stainless steel, aluminium, titanium, magnesium or platinum. As part of a funded project (funding by the German Federal Ministry of Education and Research) [4] numerous studies on vault structuring and secondary forming of perforated sheet metals were conducted in close cooperation with the project partner Friedrich Graepel AG. Perforated sheet metals allow only comparable small degrees of deformation, since the notch stresses in the bars (between the holes), can rapidly result in fracture. Since the vault-structuring process is very gentle, even perforated sheets with very large free cross sections (up to 80%) and thus very thin bars can be vault-structured. Vault-structured perforated sheet metals with a high rigidity at low weight may be used as semi-finished products for several applications.

The preserved formability of vault-structured perforated sheet metal allows a secondary forming to 3D-shaped components [4] (Figure 7). Additionally fibrous materials like paper/ cardboard and fibre reinforced plastics can be stiffened by vault-structures even though their formability (especially the elongation) is very limited [5] (Figure 6).

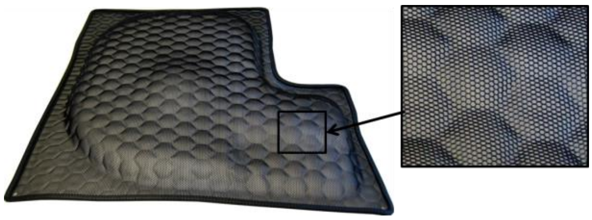


Figure 7 : Demonstrator of a 3D-shaped, vault structured, perforated sheet metal (Graepel AG) [4]

3 PROPERTIES OF VAULT-STRUCTURED MATERIALS

Vault-structures advantageously enable synergetic properties for sheet materials. In addition to the increased bending and buckling stiffness further synergetic performance characteristics occur:

The increase of bending stiffness and consequently the material savings potential can be quantified by 3-point bending tests. The deflection of the sheet metals and the corresponding forces are shown in the diagram of Figure 8. Compared to the unstructured sheet metal of same grade, and wall thickness, the bending stiffness of a vault-structured sheet in the preferred direction (corresponds to the zig-zag direction of the hexagonal folds) is up to seven times higher (stiffness factor). Perpendicular to the preferred direction the stiffness factor is about ½ or ⅓ compared to the preferred direction. A comparison with conventionally structured sheets (Knobbed) shows that the bending stiffness of vault-structures is increased in the preferred direction by a factor of approximately three (Figure 8). This ratio turns out even more positive for the vault-structures in case of high strength and brittle metals, because by conventional embossing only significantly shallower structures (with less increased bending stiffness) can be produced compared to the gentle vault-structures.

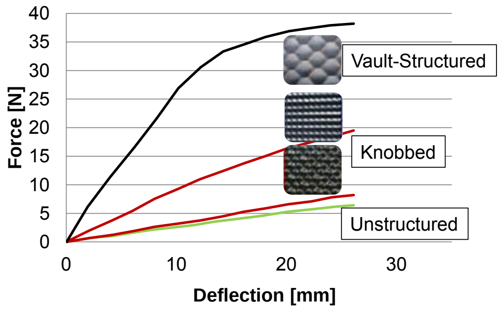


Figure 8 : Results of 3-Point-BendingTests (Steel DC04)

To quantify the local plasticisation in vault-structures a correlation of local Vickers-hardness and elongation (obtained from tensile test) was used. Due to the strain hardening during forming, the Vickers-hardness increases with larger strains. A boundary for the minimum and maximum local Vickers-hardness/ plasticisation is obtained by the Vickers-hardness of the unstructured sheet metal (no deformation; lower horizontal green lines in Figure 9) and the Vickers-hardness of the unstructured sheet after fracture in the tensile test (maximum deformation, upper horizontal red lines in Figure 9). A stainless steel sheet metal with embossed hexagonal structures of a competitor was used for the comparison of vault-structuring and embossing relating to plastic deformation. A vault-structured stainless steel sheet metal of the same thickness and material grade was manufactured with an equivalent structure depth for comparability. For both types of structured materials, the Vickers-hardness distribution was measured several times (HV 0.2) along the paths A and B (Figure 9). The averaged values are shown in the diagrams of Figure 9. For both types of structures the maximum Vickers-hardness occurs in the region of the fold and a local maximum in the region of the mould. For the embossed sheet metal, however, approximately 85% of forming reserves are already locally used, in the case of the vault-structured sheet only about 30% of the forming reserves are locally used [6]. It is shown that vault-structured materials preserve large reserves of formability which can be used for secondary forming operations, crash energy absorption or as a reserve for fatigue strength.

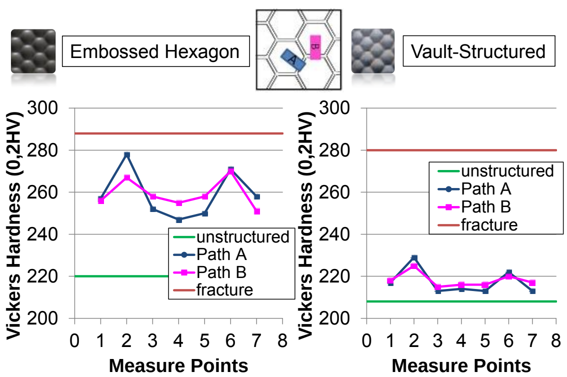


Figure 9 : Distribution of Vickers hardness of vault-structured and hexagonally embossed stainless steel sheet metal

Further synergetic properties of vault-structured materials which enable additional customer benefits are described below:

Reduced clanking and droning of thin-walled components: In vault-structured materials the low eigenfrequencies caused by acoustic excitation are shifted to higher frequencies compared to the unstructured materials. Additionally vault-structured materials also exhibit an increased logarithmic decrement, so that an acoustic vibration is much faster fading out compared to an unstructured sheet metal, as experimental studies have shown.

Preservation of surface finish: Raw materials can be economically coated with a functional layer (e.g. painting, anodizing) before the vault-structuring process. The gentle forming process doesn't reduce the surface quality.

Quasi glare-free light reflection: Used as a light reflector, each vault of the vault-structures acts as a small, curved mirror so that a diffuse, glare-free light is reflected (used in product: Hexal Lamp by Osram former Siteco).

Improved heat and mass transfer: The liquid flow over a vault-structured wall results in an alternating flowing of the boundary layer of the fluid resulting in improved heat and mass transfer of 50% to 90% in comparison to the unstructured wall. Since the vault-structures have got no sharp edges and further more the mean hydraulic flow cross-section of the pipe or channel is constant on all cross-sections (due to the evenly staggered arrangement of the structures), the pressure loss compared to the unstructured wall increases only comparatively moderate. In that way advantageous properties for apparatus of the heat and mass transfer, concerning heat or mass transfer performance, pumping energy, material costs and weight saving are generated.

4 FURTHER PROCESSING OF VAULT-STRUCTURED SHEET METALS

Vault-structured materials sometimes require a modified processing technology, so that the beneficial synergetic properties are preserved. For that reason the Dr. Mirtsch Wölbstrukturierung GmbH attaches significant importance in structure conform as well as material and surface preserving secondary forming processes. An important feature of the vault-structure conform secondary forming process is a substantially isometric deformation, which means that surface area before and after the secondary forming operation is quasi unchanged.

The 3D-contour of vault-structures is not obtained by increasing the surface area (which would result in partial thinning of the sheet metal), but by geometrical gathering, which means that surface area remains basically unchanged with no thinning of the material thickness (Figure 10, left). For secondary forming of vault-structured materials it beneficially needs to be ensured that in the areas of secondary forming an equivalent geometrical gathering is achieved as in the remaining areas. In this way, disturbing residual stresses and instabilities due to differences in lengths between the secondary-formed and initial areas of a vault structured material can be avoided.

4.1 Fine-Structures for Joining

A common requirement for the application of vault-structured sheet materials is the integration in existing constructions especially the joining in the edge regions. To design quasi planar edge regions the vault-structure conform fine-structures were developed and tested. The fine-structures are adapted to the geometry of the vault-structures in a way that a) the geometrical gathering of both structure types is quasi equivalent and b) the heights of the fine-structures is very small compared to height of the vault-structures (Figure 10, right). A simple local flattening of the edge regions of a vault-structured sheet material is not applicable. Local flattening of the vault-structured material would result in uncontrollable residual stresses and distortions caused by local geometrical stretching. Figure 10 (right) shows an example of fine-structures with a structure height comparable to the thickness of the initial sheet material.

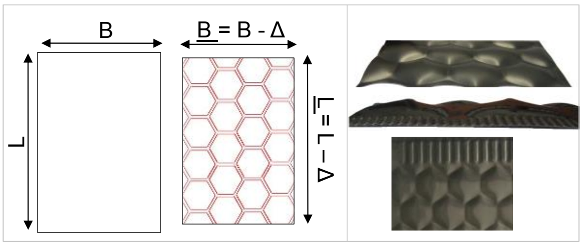


Figure 10 : Geometrical gathering of a sheet material by vault-structuring (left) and fine-structures on the edge region of a vault-structured sheet metal (right)

4.2 Bending Technique „BendHex“ for Vault-Structures

If conventional bending technique (with straight bending edge) is applied to vault-structured sheet metals, residual stresses and unwanted distortions can appear. The reason is - analogue to the local flattening of vault-structured sheet metals (see par, 4.1) – due to resulting length differences of the structured areas and the locally flattened and straightened bending edge.

A new vault-structure conform bending technique "BendHex" was developed and invented by Dr. Mirtsch Wölbstrukturierung GmbH. The curvy bend edge is designed in a way so that a) quasi no differences in lengths between the vault-structured area and the area of the bending edge occur and b) the shape of the bending edge is generated in a comparably material preserving manner (Figure 11).

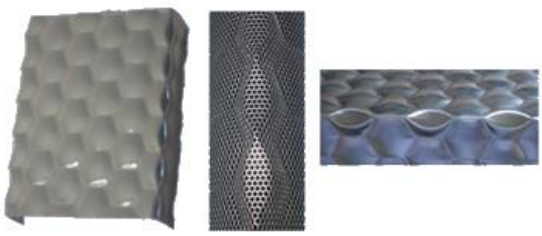


Figure 11 : Vault-structure conform bending technique “BendHex” of Dr. Mirtsch Wölbstrukturierung GmbH

Studies (experimental and FEM) have shown that the bending technique "BendHex" additionally results in a significant stiffening of the bending edge compared to conventional straight bending edges. This new bending technique can be applied on conventional bending machines equipped with special, patented bending tools (development and distribution by Dr. Mirtsch Wölbstrukturierung GmbH).

5 PRODUCTS WITH VAULT-STRUCTURES

Vault-structured products are applied in various industrial sectors. Preferably the product is enhanced by several synergetic properties of the vault-structures to increase the customer’s benefit.

5.1 Products in automotive applications

The lightweight catalyst of Emitec is equipped with vault-structures resulting in a reduction of wall thickness and thus weight reduction (Figure 12). Due to the vault-structured stainless steel cylinder a) the bending rigidity is improved (compared to cylinder with equivalent wall thickness) and b) mechanical stresses caused by rapid changes in temperature loads and thermal shocks are significantly reduced.

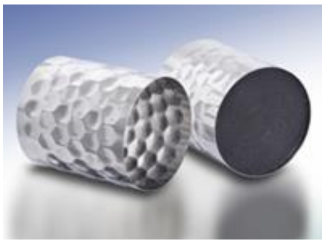


Figure 12 : Lightweight catalyst (Emitec)

The back-panel of the roadster SLK (Daimler) is equipped with vault-structures (Figure 13). The Dr. Mirtsch Wölbstrukturierung GmbH manufactures the pre-cut vault-structured sheets made from aluminium coil, which are pressed to the finished back-panel in a secondary forming operation (Gestamp). In addition to material savings the synergetic properties are a better acoustic damping behaviour and a reduced installation space needed.

Figure 13 : Back-panel of SLK (Daimler)

5.2 Product in process engineering and washing machine

With the vault-structured coiler plate CLEANcoil (Rieter) fibres like polyester are well defined placed in containers of spinning machineries at great speed (Figure 14). Using conventional coiler plates, cleaning cycles of 2-3 hours are required to remove disturbing dust or fibre particles. The vault-structures reduce the friction when the fibre is sliding over the smooth vault tops. Simultaneously unwanted dust or fibre particles are separated and collected in the folds of the vault-structures. Therefore the cleaning cycle is drastically increased from 2-3 hours to 1-7 days.

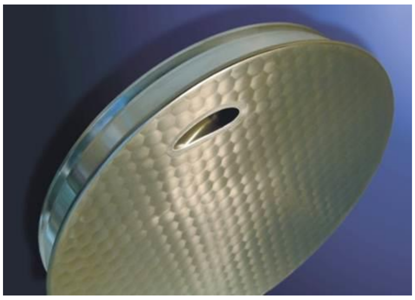


Figure 14 : Coiler plate CleanCoil (Rieter)

With the vault-structured washing drum (Miele) the laundry is particularly protected both during washing and during spinning: Due to the 3D-shape of the vault-structures a water film is generated between the textiles and the drum wall on which the textiles slide like on a cushion. Therefore, the mechanical stresses on the clothes during washing and spinning are reduced allowing a "more gentle, faster and more economical washing" (Figure 15).

Figure 15 : Miele washing-drum

5.3 Products in architecture

Vault-structured sheet metals are used in several architectural projects. Figure 16 shows a sports hall with a vault-structured roof (6.000m²) in Odessa, Ukraine. For this project the Dr. Mirtsch Wölbstrukturierung GmbH received the "German Material Efficiency Award". In a very ecological and economical way pre-coated aluminium coil material was continuously vault-structured and afterwards continuously roll-formed to standing seam profiles which were mounted on the roof. Due to the vault-structures the material thickness/ weight could be reduced, the pre-coated surface quality remained unchanged and possible dents caused by hail impact were optically camouflaged.

Figure 16 : Vault-structured roof in Odessa (Böhme Haustechnik)

For a representative building in Manhattan, USA perforated stainless steel sheet metals with vault structures were used as façade elements as shown in Figure 17.

Figure 17 : Decorative façade in Manhattan (Roy, High Line 519)

6 REFERENCES

[1] Vincent et al., 2006, RSJ Interface 3: p.471-482

[2] Paul B. Green, „Transductions to Generate Plant Form and Pattern: An Essay on Cause and Effect", Anals of Botany 78: P. 270, 1996

[3] VDI-Buch, „Technology Guide": Kapitel „Self-organisation", „Applications: Vault structures in sheet metal", ISBN 978-3-540-88545-0

[4] KMU-innovativ FKZ: 033R035A: „Ressourceneffizienz und verbesserte Produkteigenschaften durch Herstellung wölbstrukturierter, 3D-schalenförmiger, metallischer Leichtbauteile"

[5] WK Potenzial FKZ: 03WKP06C: „Energieeffiziente Leichtbauwerkstoffe, Halbzeuge und Strukturen auf Basis faserverstärkter Kunststoffe mit ausbalanciertem Eigenschaftsprofil für ausgewählte Anwendungen"

[6] International Conference Bad Nauheim „Strategies of Carbody Manafacturing" Prof. Dr. Frank Mirtsch, Dr. Mirtsch GmbH "High resource efficiency for lighter, geometrical simple body parts by Vault-structuring", March 16th/17th 2010

[7] F. Mirtsch, Drastisch höhere Steifigkeiten", Deutsches Ingenieurblatt Nr. 07-08/11, p. 22-26

GCSM 11th Global Conference on Sustainable Manufacturing
2013 23rd - 25th September Berlin - Germany

12.5 Improving powder injection moulding by modifying binder viscosity through different molecular weight variations

J. Gonzalez-Gutierrez [1], P. Oblak [1], B.S. von Bernstorff [2], I. Emri [1]
[1] Center for Experimental Mechanics, University of Ljubljana, Slovenia
[2] BASF AG, Germany

Abstract
Powder injection moulding (PIM) is a versatile technology for manufacturing small metal or ceramic parts with complex geometry. Invariably, PIM consists of 4 stages: feedstock preparation, injection moulding, debinding and sintering. Debinding is the most time consuming step and in an effort to reduce debinding times, catalytic debinding was introduced, which rely on the sublimation ability of Polyoxymethylene (POM). Besides fast debinding, POM provides excellent mechanical strength to the moulded part. One major problem of POM-based binders is their high viscosity that can complicate the injection moulding process. This paper examines the possibility of lowering the viscosity of POM without affecting its mechanical strength by changing its average molecular weight (M_w). It was observed that POM's viscosity increases with M_W at a faster rate than impact toughness and it is suggested that a M_w of around 24000 g/mol provides the most appropriate combination of strength and fluidity.

Keywords:
Impact Toughness, Molecular Weight, Polyoxymethylene, Powder Injection Moulding, Viscosity

1 INTRODUCTION

Powder injection moulding (PIM) is a technology for manufacturing complex, precision, net-shape components from either metal or ceramic powder. The potential of PIM lies in its ability to combine the design flexibility of plastic injection moulding and the nearly unlimited choice of material offered by powder metallurgy, making it possible to combine multiple parts into a single one [1]. Furthermore, PIM overcomes the dimensional and productivity limits of isostatic pressing and slip casting, the defects and tolerance limitations of investment casting, the mechanical strength of die-cast parts, and the shape limitation of traditional powder compacts [2].

Due to the demand of high performance materials and the miniaturization of complex components in various fields, PIM market is expected to reach a value $ 3.7 billion by the year 2017 [3]. Metal powder injection moulding (MIM) is still considered the largest segment of this market, accounting for more than 70% of global output. Although PIM is globally widespread, Europe and Asia-Pacific account for a major share of MIM segment, while USA is still the largest market for Ceramic Injection Moulding (CIM) [3].

PIM is generally best suited to produce parts less than 6 mm in thickness and weighting less than 100 grams [4]. Therefore, industries that demand miniaturization of complex components can benefit from using PIM in their manufacturing process; some examples of these markets are the consumer electronics, medical devices and automotive industries. In Europe, the PIM production is dominated by automotive applications and the so called consumer market (which includes watches and eyeglasses), while the North American production is mainly applied to the medical/healthcare field. On the other hand, the Asian production, considered the largest one, is dominated by consumer electronics and information technology applications [3].

When comparing manufacturing of metal parts by traditional methods, such as casting, warm extrusion and machining, with PIM, it has been found that raw materials used and energy consumption are decreased substantially. The waste is reduced due to the nature of the feedstock leftovers from the injection moulding which can be reused by re-melting the polymer matrix and feeding once again into the processing equipment. Energy consumption is reduced since parts are formed at the melting temperature of polymers rather at the melting temperatures of metals which is at least one order of magnitude higher. The latest variant, nPIM, which utilizes nanoparticles in its feedstock, could further increase the benefits of powder injection moulding by lowering sintering temperatures, producing finished parts with surfaces similar to polished products and reducing the porosity of the final part. Thus this technology could be used in high precision components or even jewellery. All of these benefits will improve the sustainability of manufacturing metal parts with complex geometry.

The process of Powder Injection Moulding (PIM), invariably, consists of four steps: I) Feedstock preparation, II) injection moulding, III) binder removal and IV) sintering [5][6]. During the feedstock preparation the metal or ceramic powder and an organic multicomponent binder are combined in a variety of compounding equipment, the mixture is then pelletized to an appropriate shape for feeding into the moulding machine. The injection moulding process is mainly identical to conventional plastic injection moulding. Nevertheless, some machine hardware changes are usually required to process a specific feedstock based on its compressibility and viscosity. A moulded part is called a “green part” and is oversized to allow shrinkage during debinding and sintering [2].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

Binder removal is one of the most critical steps in the PIM process since defects can appear due to inadequate debinding. Three main methods can be applied depending on the composition of the binder: thermal, solvent, and catalytic. Catalytic debinding is by far the fastest method of removing the binder from the moulded part; it is based on the solid-to-vapour catalytic degradation of polyoxymethylene (POM), which occurs when such polymer is exposed to high enough temperatures (110 to 150 °C) in the presence of nitric or oxalic acid vapour. Sintering is the last stage of the PIM process; it is a thermal treatment that transforms metallic or ceramic powder into bulk material with improved mechanical strength that in the majority of cases has residual porosity [7].

The feedstock material used in PIM has two main contradictory requirements; first, the feedstock should have low viscosity at the moulding temperatures (190 to 210 °C), and second, it should have good mechanical (e.g. high toughness) properties in the solid state (>160 °C) before debinding. Currently available POM-based feedstock materials fulfil the second requirement very well; however, the first condition, which is related to processability, is partially not meet since neat POM has much higher viscosity than other binders based on polyolefins [7]. It has been suggested that the binder should have a viscosity lower than 10 Pa s at a shear rate of 100 s^{-1} [8], which is 20 times lower than currently available POM-based binders. In order to reduce the viscosity of POM-based binders, blending of POM with other polymers has been investigated but the viscosity is still orders of magnitude higher than other binders [7]; therefore other methods are needed to reduce the viscosity of POM-based binders. Another way to lower the viscosity of polymers is to lower their molecular weight [9][10][11], thus in an effort to decrease the viscosity of binders used in PIM, POM materials with distinct molecular weights have been synthesized and their viscosity and impact toughness have been investigated.

The goal of this paper is to determine the maximum molecular weight of POM that will provide adequate viscosity (<10 Pa s) without compromising its toughness. The viscosity which is directly linked to the processability of the feedstock in the injection moulding machine, while the toughness is linked to the mechanical strength of the moulded parts that can influence the way these parts are handled before sintering. Lowering the viscosity of feedstock materials will further decrease the energy consumption during injection moulding, which in turn will make PIM a more sustainable manufacturing technique.

2 MATERIALS AND METHODS

2.1 Materials

For this investigation 8 POM copolymers with different average molecular weights were synthesized by BASF (Ludwigshafen, Germany). The nomenclature and average molecular weight of all the POM materials used in this study is shown in Table 1. Molecular weights were measured by the supplier using gel permeation chromatography (GPC) and it has been reported that all materials are heat stable, showing no de-polymerization or polymerization after melt processing.

Table 1. Average molecular weight of POM copolymers

Copolymer ID	Average Molecular Weight, M_w, [g/mol]
M_W1	10240
M_W2	24410
M_W3	36340
M_W4	60500
M_W5	81100
M_W6	92360
M_W7	109000
M_W8	129300

2.2 Viscosity measurements

Small amplitude oscillatory measurements were performed to determine the viscosity of POM copolymers. Measurements in oscillatory mode were performed in a Haake MARS-II (Thermo Scientific, Germany). Two frequency sweep tests were performed at 190 °C, using a truncated cone-plate geometry (diameter = 20 mm, gap = 0.054 mm). During the first sweep, the frequency was increased from 0.01 Hz (0.0628 rad/s) to 100 Hz (628.32 rad/s) in 25 increments equally spaced in the logarithmic scale; while during the second one, the frequency was decreased from 100 Hz to 0.01 Hz. All measurements were performed applying a shear stress of 100 Pa, previously determined to be within the linear viscoelastic region of all materials. All viscosity measurements were performed six times per material. In this study, viscosity results are presented as the magnitude of the complex viscosity ($|\eta^*|$), which is related to the constant rotational viscosity (η) through the Cox-Merz rule (1) [12], which is shown to apply for POM in Figure 1.

$$|\eta^*(\omega)| \approx \eta(\dot{\gamma}), \text{ when } \omega = \dot{\gamma}, \quad (1)$$

where ω is the angular frequency in rad/s and $\dot{\gamma}$ is the shear rate in 1/s.

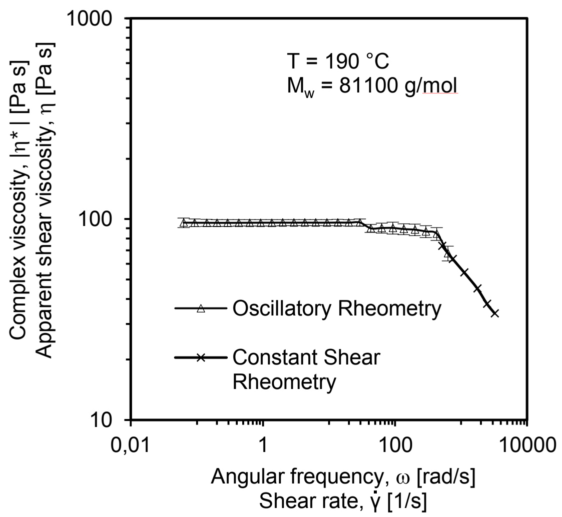


Figure 1. Applicability of Cox-Merz rule for POM

2.3 Impact toughness measurements

Charpy tests were performed at room temperature in order to measure the impact toughness of all selected POM copolymers. Non-notched cylindrical specimens were prepared via twin screw extrusion in a PolyLab Haake OS (Thermo Scientific, Germany). A glass tube (external diameter = 9 mm, internal diameter = 6 mm and length = 200 mm) was placed at the end of the extrusion die and filled with the extrudate up to a minimum length of 80 mm. The melt temperature at the die was measured to be 190 °C. After extrusion, extrudates were left to cool to room temperature inside the glass tube for at least 4 h before performing the impact tests. Two hammers were used, 1 and 3.9 J, which provide an estimated impact velocity of 2.7 and 2.8 m/s, respectively. All measurements were repeated six times.

3 RESULTS AND DISCUSSION

3.1 Viscosity

The magnitude of the complex viscosity as a function of angular frequency for all the different POM materials is shown in Figure 2. It is clear that as Mw increases so does the viscosity, also it can be seen, that almost all of the materials investigated display Newtonian behaviour in the frequency range investigated. Only the materials with the higher molecular weight (M_W6 to M_W8) show a clear deviation from Newtonian to shear thinning behaviour starting at approximately 30 rad/s. This is not unexpected, since as the molecular weight increases, it is expected that the level of entanglement increases and the amount of free volume decreases, which reduce the chain mobility and as a consequence increases the viscosity [13]. However, as the frequency of excitation or shear rate increases these entanglements break and the viscosity starts to decrease, i.e. shear thinning behaviour. Polymers with higher M_w have a higher number of entanglements and thus are more susceptible to shear leading to an onset of shear thinning at lower frequencies, as observed in Figure 2.

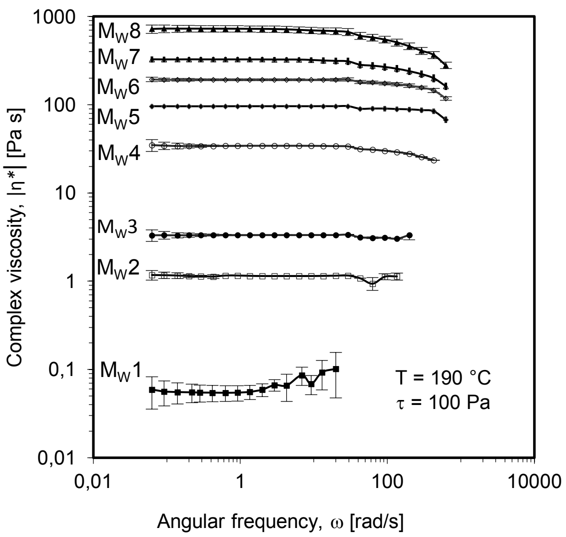


Figure 2. Viscosity of POM copolymers with different average molecular weights, M_w

Polyoxymethylene can be classified as a linear entangled polymer and it is well known that for this type of polymers the shear Newtonian viscosity, η_0 and the average molecular weight, M_w are related by a power law function (2) of the form proposed by Fox and Flory [11]:

$$\eta_0 = K\, M_w^b\,, \qquad (2)$$

where the K parameter quantifies the temperature and pressure dependence of the Newtonian viscosity of molten polymers, and a is related to the level of entanglement of the polymers, for the conditions here tested K = 5 x 10^{-17}. Figure 3 shows that the above equation applies also for the POM copolymers here investigated. The value of b has been reported for several polymers to be between 3.3 and 3.7 when Mw > Mc and b ≈ 1 when $M_w < M_c$, where M_c is a critical average molecular weight [13][14][15]. Below M_c the flow units are single macromolecules while above M_c the flow units are chain segments since the macromolecules are entangled [14]. As can be seen in Figure 3, all the POM copolymers investigated appear to be above the critical molecular weight, since the value of b is approximately 3.7; this was expected since it has been estimated in the literature that the molecular weight for entanglement M_e of POM is 3100 g/mol [16] and it is generally believed that M_c is between 2 and 3 times larger than M_e [13][14][15]. In this particular study the lowest molecular weight available is around 10000 g/mol, which is more than 3 times the estimated molecular weight for entanglement, M_e.

With respect to the viscosity required for PIM (< 10 Pa s), it appears that one could select a POM material with an average molecular below or equal to 36340 g/mol, i.e. M_W1, M_W2 and M_W3. However, the decision cannot be taken without considering the solid mechanical properties of the polymer, in particular the impact toughness of the material, since it is desirable that the moulded part exhibits good toughness in order to be easily handled after injection moulding without fracturing.

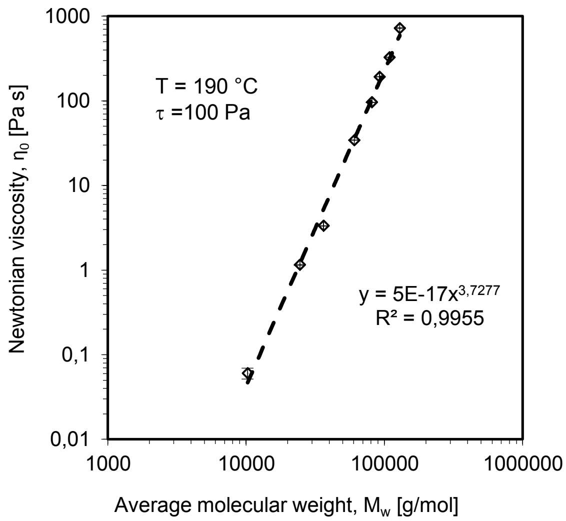


Figure 3. Effect of average molecular weight, M_w, on viscosity of POM copolymers

3.2 Impact toughness

It is known that the impact toughness of polymeric materials is highly dependent on the molecular weight. When the molecular weight of polymers is increased, the mechanical response goes from brittle to ductile [17], i.e. the toughness increases with molecular weight [18]. For semi-crystalline polymers, like POM, this increase has been attributed to an increase in density of inter-lamellar tie chains and chain entanglements, which give higher craze fibril strength and, hence, a higher energy for fracture initiation is required [19]. Figure 4 shows that for POM, a similar behaviour has been observed, as the molecular weight increases the impact toughness increases: in the range between 10240 to 24410 g/mol the increase is very small and it appears that a plateau is present between 24410 and 60500 g/mol; and finally as the M_w increases beyond 60500 g/mol the increases in toughness is very pronounced. Similar behaviour has been reported in other polymers with respect to their mechanical strength [20]. It has also been reported that as the molecular weight increases beyond a very large molecular weight a decrease in the fracture toughness can be observed as in the case of ultrahigh molecular weight polyethylene, thus toughness is a nonmonotonical function of molecular weight with a maximum [20]. In this particular case, the maximum was not reached in the range of molecular weights investigated.

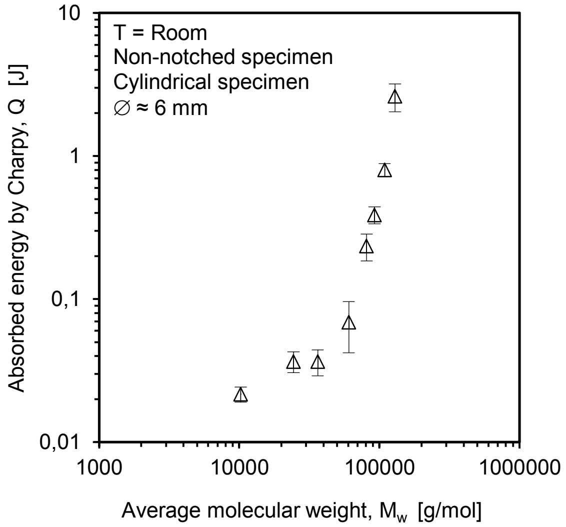


Figure 4. Effect of average molecular weight, M_w, on impact toughness of POM copolymers

3.3 Binder selection

In order to select the POM material to be used as part of the PIM binder, it is important to take into account the viscosity of the material as well as its toughness. The viscosity should be as low as possible to allow easy moulding, while the toughness should be as high as possible to prevent damage to the moulded part before sintering. As it can be seen in Figure 5, the viscosity increases much more rapidly than the toughness; viscosity increases approximately 6 orders of magnitude, while at the same time the toughness increases only 3 orders of magnitude. Figure 6 also shows that the dependence of toughness (absorbed energy by Charpy) with viscosity follows a similar shape as its dependence with average molecular weight (Figure 5), showing a plateau at the viscosity values between 1 and 30 Pa s, which correspond to an average molecular weight between 24410 and 60500 g/mol (M_W2 and M_W4); therefore by looking at these results it can be suggested that POM M_W2 should be used as the main component for the binder since it has 3 times lower viscosity than POM M_W3, but the same level of toughness. It is important to mention that the POM currently used as binder for PIM feedstock has a similar molecular weight to M_W6, thus if we select M_W2 as the new binder we can expect a decrease in viscosity of almost 200 times, while a decrease in toughness of approximately 10 times, which can be considered a significant improvement.

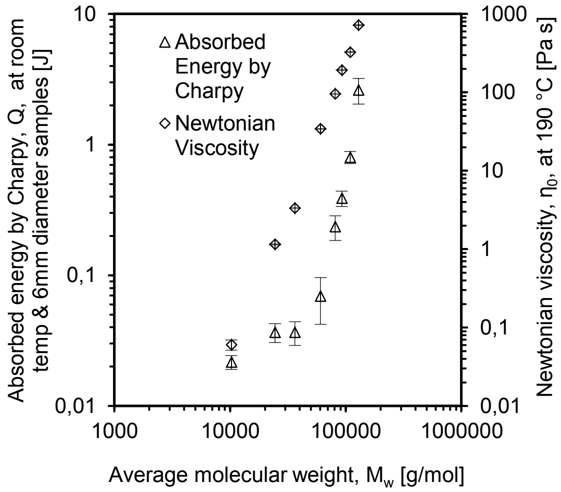


Figure 5. Effect of molecular weight, M_w, on viscosity and impact toughness of POM copolymers

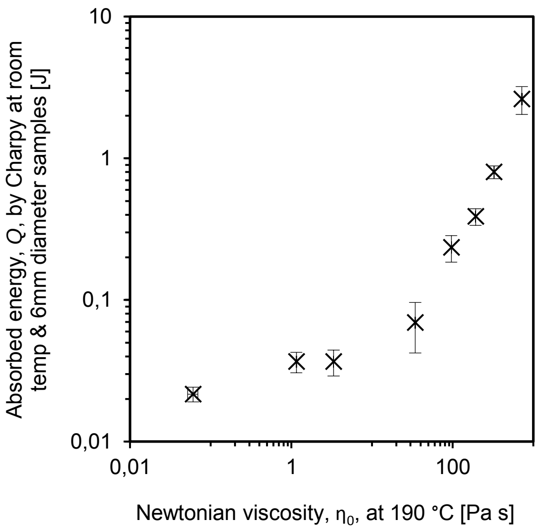


Figure 6. Impact toughness measured by Charpy as a function of Newtonian viscosity for POM copolymers

4 CONCLUSIONS

POM used as a binder for powder injection moulding (PIM) has the major advantages that it can undergo catalytic debinding which is much faster than other debinding processes and that the moulded part has good mechanical strength (i.e. high toughness). However, currently used catalytic binder has high viscosity that can bring difficulties to the injection moulding process. In this investigation the viscosity and toughness of different POM copolymers has been studied [22].

It has been observed that both properties increase as the average molecular weight M_w increases. However, the viscosity increases much more rapidly than impact toughness. Viscosity increases with molecular weight as a power law function, with an exponent a ~ 3.7, as it has been reported for other polymers [13][14][15]. Therefore, for an increase in M_w of approximately 10 times there is a viscosity increase of almost 12000 times. The impact toughness measured by Charpy tests increases approximately 130 times as the M_w increased from 10240 to 129000 g/mol. The increase in toughness does not follow a simple relationship with molecular weight and it appears that there is a plateau at small molecular weights.

With the information here gathered, it possible to suggest that a POM copolymer with an average molecular weight of around 24000 g/mol could be used as the main component of a binder used in PIM. As compared to the currently available binder, using POM with the suggested M_w can lead to a decrease in viscosity of 200 times, while reducing toughness only by 10 times; this can be considered a significant improvement on the performance of POM-based binders for PIM [22] and a step in the right direction for the sustainable manufacturing of metal parts with complex geometry, since there will be a reduction on energy consumption during the injection moulding process.

5 ACKNOWLEDGEMENTS

This research work is co-funded by Slovenian Research Agency - *ARRS*, and the Slovene Human Resources and Scholarship Fund - *Ad futura*.

6 REFERENCES

[1] Hausnerová, B., 2011, Powder injection moulding- An alternative processing method for automotive items. In New Trends and Developments in Automotive System Engineering, Chiaberge M. (Ed.), InTech, Croatia, 129-145.

[2] Tandon, R., 2001, Metal injection moulding. In Encyclopedia of Materials: Science and Technology, Buschow, K.H.J., Cahn, R.W., Flemings, M.C., Ilscher, B., Kramer, E.J., Mahajan, S. & Veyssiere, P. (Ed.), Elsevier Science Ltd, Netherlands, 5439-5442.

[3] GIA, 2011, Metal and Ceramic Injection Molding. Global Industry Analysts, Inc., San Jose, CA.

[4] Boljanovic, V., 2010, Powder metallurgy. In Metal Shaping Processes: Casting and Molding, Particulate Processing, Deformation Processes, Metal Removal, Industrial Press Inc., New York, NY, 75-106.

[5] Gonçalves, A.C., 2001, Metallic powder injection molding using low pressure. J. Mater. Process. Technol., 118, 193-198.

[6] Tay, B.Y., Loh, N.H., Tor, S.B., Ng, F.L., Fu, G. & Lu, X.H., 2009, Characterisation of micro gears produced by micro powder injection moulding. Powder Technol., 188, 179-182.

[7] Gonzalez-Gutierrez, J., Stringari, G.B., Zupančič, B., Kubyshkina, G., von Bernstorff, B., Emri, I., 2012, Time-dependent properties of multimodal polyoxymethylene based binder for powder injection molding. Journal of Solid Mechanics and Materials Engineering, 6, 419-430.

[8] Mutsuddy, B.C., Ford, R.G., 1995, Ceramic Injection Molding, Chapman & Hall, London, U.K., 1-26.

[9] Nichetti, D., Manas-Zloczower, I., 1998, Viscosity model for polydisperse polymer melts, J. Rheol, 42, 951-969.

[10] Kanai, H., Sullivan, V., Auerbach, A., 1994, Impact modification of engineering thermoplastics. J. Appl. Polym. Sci., 53, 527-541.

[11] Fox, T.G., Flory, P.J., 1951, Further studies on the melt viscosity of polyisobutylene. J. Phys. Colloid Chem., 55, 221-228.

[12] Cox, W.P., Merz, E.H. 1958, Correlation of dynamic and steady flow viscosities. J. Polym. Sci., 28, 619-622.

[13] Grosvenor, M.P., Staniforth, J.N., 1996, The effect of molecular weight on the rheological and tensile properties of poly(ε-caprolactone), Int. J. Pharm., 135, 103-109.

[14] Colby, R.H., Fetters, L.J., Graessley, W.W., 1987, Melt viscosity-molecular weight relationship for linear polymers. Macromolecules, 20, 2226-2237.

[15] Ajroldi, G., Marchionni, G., Pezzin, G., 1999, The viscosity-molecular weight relationships for diolic perfluropolyethers. Polymer, 40, 4163-4164.

[16] Plummer, C.J.G., Cudré-Mauroux, N., Kausch, H.H., 1994, Deformation and entanglement in semicrystalline polymers, Polym. Eng. Sci., 34, 318-329.

[17] Han, Y., Gang, X.Z., Zuo, X.X., 2010, The influence of molecular weight on properties of melt-processable copolyimides derived from thioetherdiphthalic anhydride isomers, J. Mater. Sci., 45, 1921-1929.

[18] Garlotta, D., 2001, A literature review of poly(lactic acid). J. Polym. Environ, 9, 63-84.

[19] Andreassen, E., Nord-Varhaug, K., Hinrischen, E.L., Persson, A.M., 2007, Impact fracture toughness of polyethylene materials for injection moulding. Extended abstracts for PPS07EA, Gothenburg, Sweden.

[20] Baltá Calleja, F.J., Flores, A., Michler, G.H., 2004, Microindentation studies at the near surface of glassy polymers: influence of molecular weight. J. Appl. Polym. Sci., 93, 1951-1956.

[21] Nakayama, K., Furumiya, A., Okamoto, T., Yagi, K., Kaito, A., Choe, C.R., Wu, L., Zhang, G., Xiu, L., Liu, D., Masuda, T., Nakajima, A., 1991, Structure and mechanical properties of ultra-high molecular weight polyethylene deformed near melting temperature. Pure Appl. Chem., 63, 1793-1804.

[22] Gonzalez-Gutierrez, J., Oblak, P., Bernstorff, B.S., Emri, I., 2013, Processability and mechanical properties of polyoxymethylene in powder injection molding, 2013 SEM Annual Conference and Exposition on Experimental and Applied Mechanics, Lombard, IL.

12.6 Sustainable manufacturing of near net shaped engineered flexible fibrous structures for high value applications

Mohit A. Raina, Thomas Gries
Institut für Textiltechnik RWTH Aachen University, Germany

Abstract
This paper discusses various manufacturing and production technologies in the field of textiles and engineered fibrous structures. Processes have been listed which help in the development of high value added products with a feature of sustainability. The work talks about case studies which have been implemented as best practices for the fields of self-optimized machinery, processing of recycled fibrous structures from high modulus fibres and energy efficiency in textile production processes.
Keywords:
Self-optimized, Cognition, Textile, high modulus fibre, yarn, energy

1 INTRODUCTION

Textiles, as flexible and anisotropic material offer an array of possibilities for applications, where characteristic attributes such as drapability and strength of material are desired. The technologies used for the manufacture of such material are also complicated. The need for the development of new technologies and manufacturing systems for the processing of the textile fibres is a challenge. This paper discusses various manufacturing and production technologies in the field of textiles and engineered fibrous structures. Processes have been listed which help in the development of high value added products with a feature of sustainability. The work talks about case studies which have been implemented as best practices for the following field:

1.1 Self-optimized machines for better material efficiency

For high wage countries in the European continent, integrative production technologies have been developed which help in production of high value applications like technical textiles. These integrative technologies involve the implementation of sensors and actuators on machines which help in regulating the material consumption and at the same time help in producing low degrees of waste. A case with a spinning and a weaving machine will be presented along with a vision for the future of the textile industry in Europe

Objective – To enable machines with self-optimizing characteristics to provide high quality products consistently at very high productivities. The airjet spinning technology offers itself as a high productive technology for the application of self-optimization

1.2 Processing of recycled fibrous structures in applications like high modulus fibres (after life wind mills)

The processing of high modulus fibres in a 2nd life is the focus of this field. Sectors such as transportation and renewable energy production use a lot of fibres such as glass and carbon for reducing the weight and hence consumption of fuel. There are very few manufacturing technologies till date which deal with the afterlife processing and recycling of such new materials. Cases will be presented on manufacturing concepts dealing with the recycling of the high modulus fibres

Objective – Engineering fibre structures with recycled fibres to attain at least 50% the structural properties of virgin material. Here the focus lies on the development of production technologies and analysis of material characteristics.

1.3 Energy efficiency in the production process

The textile industry is a very energy intensive industry. There have been multiple approaches defined for the reduction of energy in the processing of these fibrous materials. A few cases will be presented which look at the overall production process and the methods of saving energy.

Objective – The textile industry is traditionally a very energy intensive industry. Approaches like self-optimization which reduces wastages and the approach of developing production technologies for recycled material render avenues for energy efficiency in the entire process cycle of materials. The mentioned solutions in chapter 2 and chapter 3 offer possibilities for energy efficiency.

1.4 Summary

This paper summarizes some of the manufacturing technologies which help in providing near net shaped material structures sustainably. In the first case a control system has been mentioned which helps in providing sustainable quality with the reduction in energy costs due the implementation of the airjet spinning technology. Secondly a novel processing of high modulus fibres to give them a second life and hence increase sustainability has been briefly described.

2 SELF-OPTIMIZED MACHINES FOR BETTER MATERIAL EFFICIENCY

2.1 Introduction

In order to live up with the high quality demanding market, new intelligent machine elements need to be developed which help in online quality control and also process im-

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

provement. Within the framework of many different projects at ITA, various such intelligent machine elements have been developed. Among others is the development of a control system for a spinning machine.

2.2 Control system for an Airjet spinning machine

The airjet spinning process is one of the most modern processes for the conversion of staple fibres such as cotton, polyester etc. into spun yarns [1]. The process was introduced by the Murata in 1997 and the technology has established itself over the years. The technology can be used for processing yarns at 400m/min. The yarn produced has to meet certain quality conditions. The research hypothesis and the avenues of research are mentioned in the figure 1.

The yarn quality plays a very important role. The yarn quality is one of the most important factors deciding the further processing of the rolled goods. One of the important factors defining yarn quality is the yarn evenness [2]. The yarn evenness is measured as mass per unit length. The spinning machines in a spinning mill can deliver constant yarn quality only if they are presented with raw material which is constant in mass per unit length. In order to improve the quality of the raw material in the form of a sliver certain concepts can be thought about. The sliver is the end product of the carding machine and has a variation in mass per unit length between 2-3% CV_m. In order to improve this variation the slivers are doubled and drafted on the drawframes. The drawframes results in a reduction in the variation in the sliver mass per unit length [3]. This reduction is caused due to two factors viz. by doubling slivers and also by incorporation of a closed loop control system on the drawframes. The closed loop control systems help for the elimination of faults which have been brought in by the machines [4].

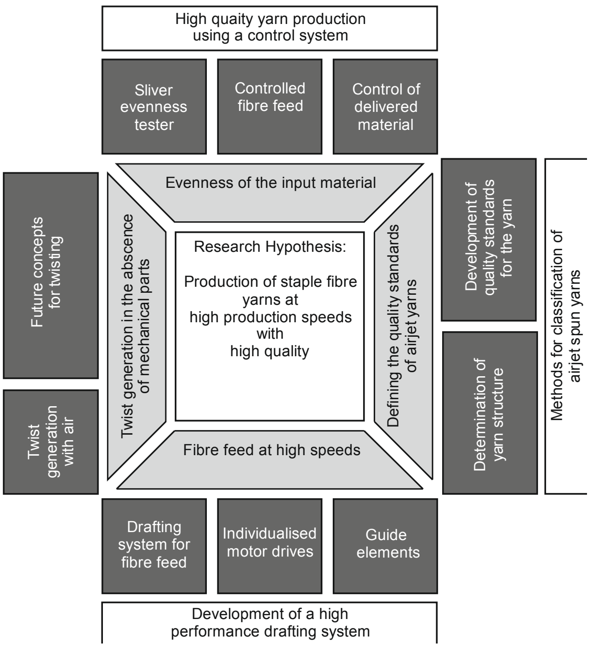


Figure 1 : Concept of the research in airjet spinning process [5,6]

2.3 Application of control systems in the drafting zone

A drafting system plays a crucial role in the airjet manufacturing process of spun yarns. The drafting system is a component of the machine where the fibres are attenuated before a twist is given to the staple fibres. In order to regulate the quality of the input material in a drafting system a control system was developed which helps in regulating the input sliver into the high speed drafting machine. The evenness of the sliver is measured by the means of a sliver evenness measuring assembly [7]. The measured mass per unit length is measured as a function of the thickness of the sliver. This is based on the work carried out in [8]. The variations are then corrected by means of the drafting system. A schematic diagram with a picture of the drafting system is seen in figure 2.

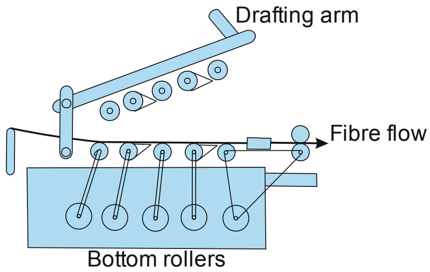


Figure 2: Schematic diagram of a drafting system

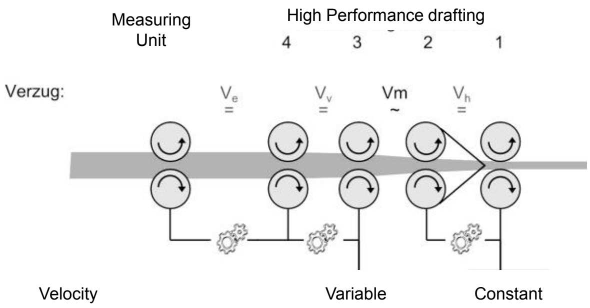


Figure 3 : Control system for the drafting system

Figure 3 shows a control system which has been implemented in the work. This control system comprises of a measuring unit which measures the thickness of the input sliver and the speeds of the subsequent drafting rollers 1-4 are regulated. The major change of draft is accounted in the zone V_m.

In order to test this drafting system a sliver with a pre-set thickness was fed as inputs. The results of the application of the controlling system were measured in terms of yarn evenness which is measured at the delivery. The results are shown in figure 3 and 4. Figure 3 shows that there is no change in the speed of the bottom roller even when the mass per unit area/ thickness is changed. This results in the production of a faulty yarn which is depicted by the decrease in the yarn fineness. Figure 4 however shows the change in bottom roller speeds and thus resulting in the regulation of the delivered material. The system varies the speed thus keeping the yarn quality constant.

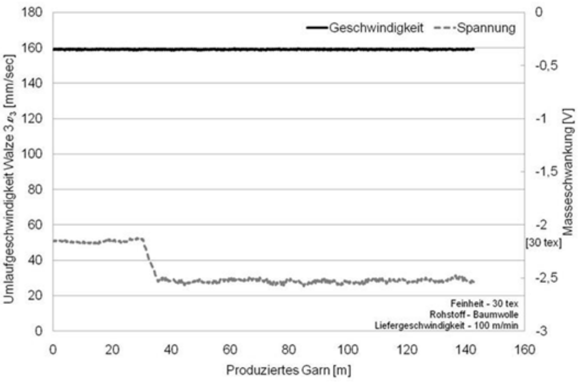


Figure 3: Uncontrolled drafting system

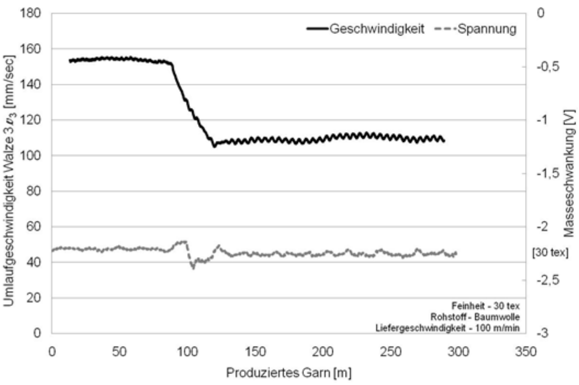


Figure 4 : Controlled drafting system

3 PROCESSING OF RECYCLED FIBROUS STRUCTURES IN APPLICATIONS LIKE HIGH MODULUS FIBRES (AFTER LIFE WIND MILLS)

3.1 Introduction

The Carbon fibre Market

The global carbon fiber market has grown over the last 5 years and is forecasted to grow to $2.3 billion in 2015 from $1.1 billion in 2009, according to Lucintel. In 2010, the global carbon fiber market is expected to have a positive growth of 8.4% mainly to demand growth in every segment. The Continuous Fiber Reinforced Thermoplastics market has experienced significant growth during last 5 years and is expected to reach $188.7 million in 2014 with a global growth rate of 10% for the next five years. The data shows that the carbon fibre industry and also the Continuous Fiber Reinforced Thermoplastics industry would render solutions to a number of fields. Today, most carbon fiber still finds its way into aerospace applications, such as the new A380 and 787 Dreamliner, but carbon fiber use is increasing in industrial applications. The Boeing 787 contains 50% of total weight in composites, the remainder being 20% aluminum and 30% titanium. The Airbus A380 contains 25 –30 tonnes of composites, 85% of which are Continuous Fiber Reinforced Thermoplastics. Continuous Fiber Reinforced Thermoplastics helps tackle problems of fuel consumption and also would offer light weight constructions. However these products with the continuous carbon fibre are at the start of their product life cycle. An end of life phase is awaited in the coming years, which would lead to generation of immense carbon fibre waste which needs to be recycled or reprocessed.

Virgin carbon material is very costly to produce in fiber shape, and possibilities need to be investigated to reclaim the fiber. Current estimates indicate that aerospace manufacturers tend to waste around 20% of their raw material, which would usually go as waste into landfill and many a times as short fibres in blends with other fibres and SMCs. The EU legislation defines final waste as, “Treated or non-treated waste that cannot be reduced under the present state of technology to obtain valuable components or to further reduce its dangerous or polluting character”. This applies both to production waste approx. 30% of the gross quantity used by a carbon-processing companies and end-of-life disposal of products. Disposal of this C - final waste currently costs around € 90 per ton, and the manufacturer has a legal responsibility to arrange the treatment and/or disposal. Hence the magnitude of the problem of restoring the carbon fibre and reutilizing it is immense.

The glass recycled fibre industry has a similar story. The material is currently being used as fillers in the construction industry. There is also an absence of production process and process parameters for their end use in nonstructural as well as structural composites.

The Glass fibre market

Nowadays glass fibers are by far the most important reinforcement material.

The worldwide consumption of glass fiber is estimated at almost 4 million tons in 2011 with a yearly grow of 7% in production capacity. In particular, some sectors like wind power energy strongly require GFRP and have a grown of around 25-30% per year.

The directive 2000/53/EC, for instance demands stringent recycling quotas for end-of-life passenger vehicles. The directive 99/31/EC bans plastic materials from disposal. The only practicable GFRP waste disposal is actually incineration. Fiber reinforcement is around 50%-70% in the main GFRP. The incineration process will melt the glass fibers. The glass slag sticking to the chamber walls of the incinerator will raise the maintenance costs. Japan’s Recycling and Treatment Council for example decided that the costs for the cleanup of the furnace must be repaid from the automotive industries in case that the car components consist of glass fiber reinforced plastics (Naitove, 2006). Moreover, the heating value of GFRPs is very low and produces a big amount of inorganic bed ash.

Actually the GFRP scraps are integrated in the cement production (principally by Geocycle, Zajons and Holcim). Other companies have been founded to recycle GFRP as filler produced by mechanical process (ERCOM GmbH 400 tons/y, Mecelec composite recycling facility, 400-600 tons/y, Plastic Omnium, Filon Products and Hambleside Danelow Limited).

Only a company operating until 2006 (ReFiber ApS from Denmark) tried to recover the fibers from wind blades preserving their geometry and their quality. Using a pyrolysis process the matrix was separated from the reinforcement so that long fibers could be recovered and recycled as secondary raw material in non-woven thermal isolator in buildings.

The development of new processes able to recover the fiber reinforcement and to engineer the recycled material in valuable products is becoming necessary as long as metals and other heavy materials have been substituted by glass and carbon fibers reinforced plastics. So far, no proper glass fiber recycling from GFRP has been successfully applied. Nowadays, the recycled glass fibers are getting relevant many industrial sectors like automotive, wind power, aircraft and buildings that must.

Objective

- To determine fibre characteristics (ideal spin finish, ideal length, fibre surface modifications etc.) with the influence of processibility of fibres for different nonwoven processes
- Engineering fibre structures with recycled fibres to attain at least 50% the structural properties of virgin material
- To determine and adapt suitable nonwoven processing methods for fibre conversion into nonwoven mats for processability as composites
- Developing nondestructive methods to evaluate fibre structures of nonwovens made of recycled fibres

Expected Results

- A knowledge matrix of fibres with suitable finish, ideal length and fibre surface modification for their processibility using different nonwoven processes
- A modeling tool to engineer regenerated fibre structures to attain 50% of the structural properties of virgin materials
- Product categories and product catalogues for nonwovens processed with various nonwoven processing technologies
- Programming a measuring technique to determine fibre orientation and evenness of nonwoven for nonwoven structures made from different processes

3.2 Concept of the work

The concept helps understand the motivation of carrying out recycling of the high modulus fibres. Starting from the centre of the concept diagram in figure 5, the reason "why" the fibres need to be processed is defined. Further on the "how" do we do the recycling has been generically mentioned and finally "what" could be done within the scope of the project has been explained. The entire concept provides an insight in the need of the recycling, the complexities of the recycling and finally the deeds to be undertaken to understand the "recycling of high modulus fibres"

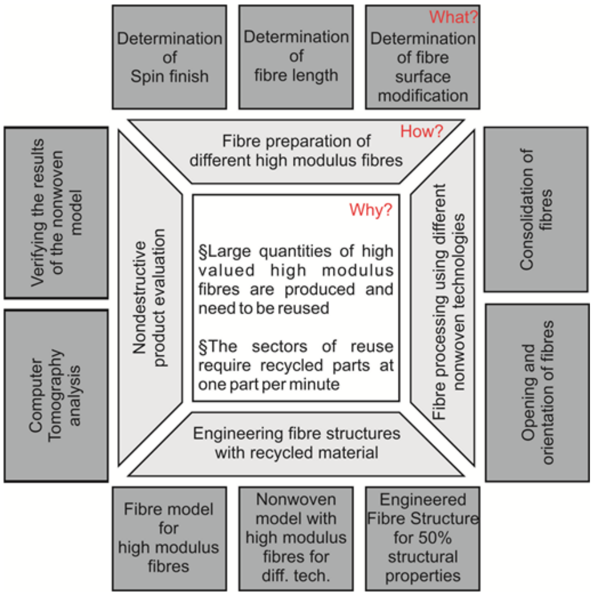


Figure 5: Concept diagram for recycling of high modulus fibres

3.3 Initial trials

The initial trials for the recycling of high modulus fibres is carried out using the airlay nonwoven system. The airlay method helps in the random distribution of fibres and the generation of an isotropic mesh of high modulus fibres.

Basis weights of between 100 – 200 gsm could be achieved using this technique. One of the major challenges though is the very poor mechanical strength of such nonwovens. These nonwovens can be impregnated with resin to form a fibre reinforced composite which then can be used in applications such as automotive interiors.

4 CONCLUSION

The entire work defined within this paper looks into multiple facets of production of near net shaped fibrous structures. The paper shows new control systems developed for the most productive staple fibre spinning process. Another aspect which has been dealt with is the necessity to process high modulus fibres like carbon and glass. Here the different areas and avenues of further work have been defined.

5 FUTURE WORK

In the field of control systems for the high speed spinning machines, the developed system has been implemented on a conventional lab scale machine. An up-scaling of the technology to an industrial machine has yet to be investigated. One of the major challenges in the application of the control system to industrial system is the time lag between measurement of the fibre sliver evenness measurement and the application of the variation of speeds in the drafting system. Certain work also needs to be carried out for the energy consumption for the most productive airjet staple fibre spinning system.

The processing of high modulus fibres also offers various challenges. These challenges begin with the determination of fibre properties (e.g. length, strength etc.). The pre-processing required for the final processing of these fibres also deserves investigation in the studies carried out in the future. Production technologies and the related fibre reinforced composite mechanical and physical strength parameters need to also be researched in the future: The recycled material definitely has a potential for being used in a second life as parts of structural fibre reinforced components.

6 REFERENCES

[1] Lord, P.R.:
Handbook of yarn production
Boca Raton [u.a.] : CRC Press ; Cambridge : Woodhead, 2003

[2] Bechlenberg, H.; Wegener, W.:
Regelanlage zum Vergleichmäßigen von Faserbändern
Textil Praxis 14 (1959), S. 35-41, 129-132, 245-249, 359-364, 456-460, 552-556, 672-678, 774-779, 877-882

[3] Wegener, W.:
Die Streckwerke der Spinnereimaschinen
Berlin ; Heidelberg ; New York: Springer, 1965

[4] Hlava, J.:
Internal model control of textile sliver drafting process
In: Summaries volume / 14th International Conference on Process Control '03, June 8 - 11, 2003, Strbské Pleso, High Tatras, Slovakia. - Bratislava, 2003, Datei: \pc041.pdf

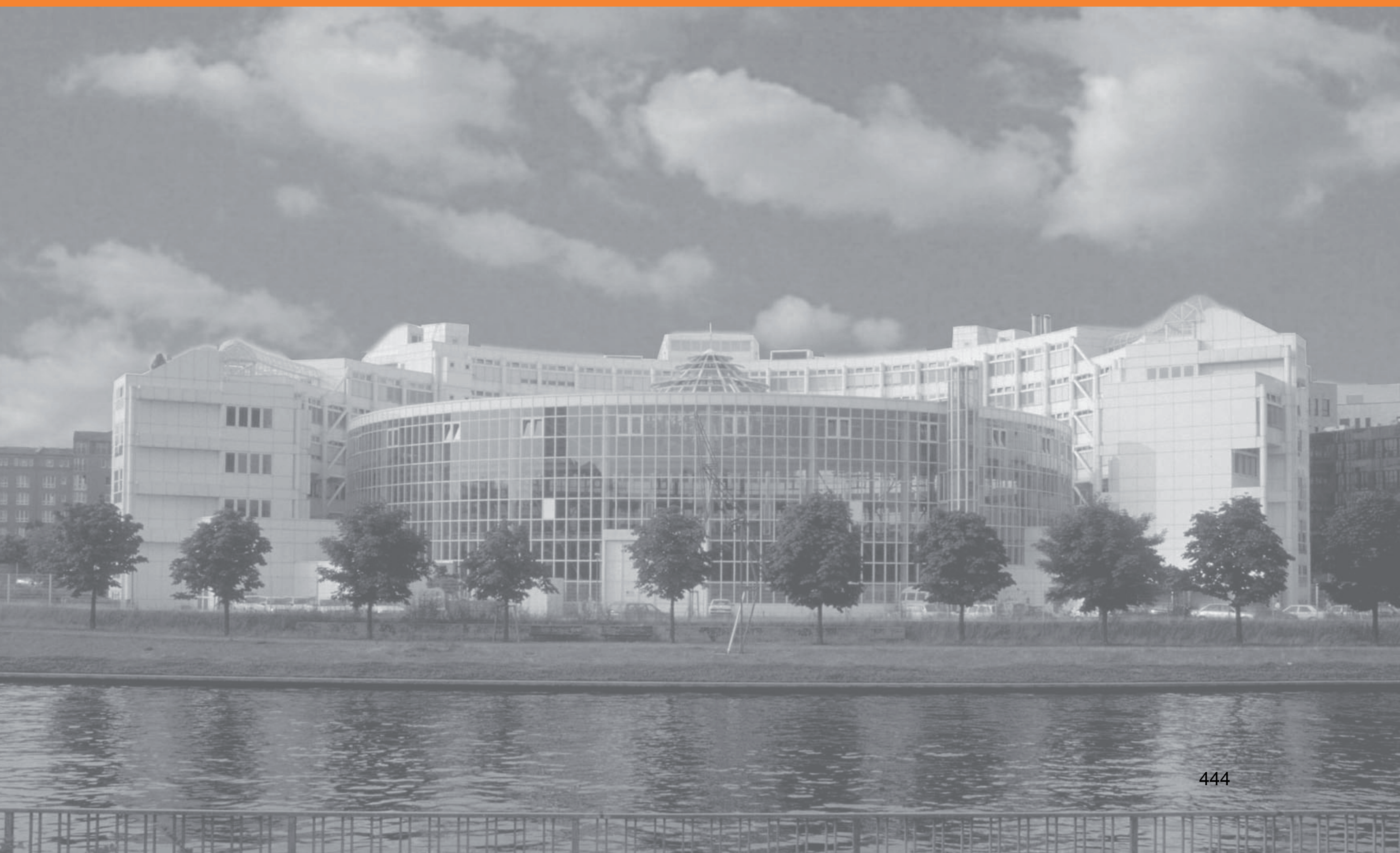
[5] Raina, M.:
Selbstregulierende Herstellung und
Klassifizierung von luftechtdrahtgesponnenen Garnen
Aachen; : Shaker, 2012 ; Zugl. Aachen, Techn. Hochsch., Diss., 2012

[6] Weide, T.:
Analyse und Simulation des Garnbildungsprozesses beim Luftechtdraht-Spinnverfahren
Aachen : Shaker, 2004 ; Zugl. Aachen, Techn. Hochsch., Diss., 2004

[7] Götzfried, K.:
Verfahren und Vorrichtung zum pneumatischen Spinnen eines Fadens. Deutsche Patentschrift DE 1056018 B, Date of issue: 23.04.1959

[8] Balakrishnan, P.:
Micro-leveler, the next generation Auto-leveler.
The Journal of the Textile Institute 98 (2007), H. 6, S. 549-557

Session 13
Design



11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

13.1 CDMF-RELSUS concept: Reliable products are sustainable products - Automotive case study "clutch"

Jens Michalski[1], Tetsuo Yamada[2], Masato Inoue[3], Stefan Bracke[1]

[1] University of Wuppertal, Chair of Safety Engineering and Risk Management, Gaußstraße 20, Wuppertal,

[2] The University of Electro-Communications, Department of Informatics, 1-5-1 Chofugaoka, Chofu-shi, Tokyo

[3] Meiji University, Department of Mechanical Engineering Informatics, 1-1-1 Higashi-Mita, Tama-ku, Kawasaki,

Abstract

Based on the customer's product recognition sustainability and environmental protection become key sales arguments within the automotive industry. Thereby customer expects reduced resource consumptions, environmental friendly manufacturing and optimised long usage phase. Especially product reliability saves resources in many ways. One main influence regarding to sustainable life span area of products is the design of a component during the design phase and the placing of upgrades during the use phase regarding to the balance of sustainability and reliability.

This paper outlines the "Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept", substantiated by the automotive case study "clutch". Based on a typical failure symptom of a clutch disk, the linkage of former field damage causes and prospective design stages is shown. With the aid of standardised innovation cycles inside the automotive industry an assignment between long-term sustainable manufacturing and reliability of mechanical components is demonstrated.

Keywords:

Life cycle Engineering, product reliability, sustainable design, manufacturing processes, field data analysis

1 INTRODUCTION

Sustainability and environmental protection become key sales arguments, especially within the automotive industry: Thereby the customer expects reduced resources consumptions, environmental friendly manufacturing, optimized usage and assortment of raw material and long customer usage phase (product reliability). In the opposite, the customer expects functionalities, innovations and modern equipment regarding to a new automobile. In summary the customer wants a product with a high quality for use. These requirements are all required by the customer. But in general, valid for all product branches, there are some preconditioned product characteristics, which none of the customers would directly express in a quantitative way: Reliability, quality and basic functions.

Manufacturer product reliability is associated with higher development and production costs, but, especially in industries with high innovation rates, customer usage is limited to the product actuality. Therefore there are two key questions with respect to this conflict area:

a. How much product reliability and, in addition, customer usage makes sense out of the view of manufacturers, customers and environmental protection?

b. What is the quantitative impact of reliable products regarding to the reduction of resources?

To increase the customer usage phase in innovative industries enhanced development strategies have to be implemented to ensure long customer usage, environmental protection and economical aspects. One strategy is the development of reliable (increase of product reliability) and upgradeable products. Through the upgrade capability additional functions or efficient components can be integrated or replaced over the customer usage phase, which leads to an extension (cf. Fig. 1) [1]. Precondition is an adjustment of the manufacturing planning regarding to the production of wear parts and remanufacturing possibilities with regard to the extended use phase. Finally, the verification of the product reliability - and therefore the sustainable product concept - can be based on field data.

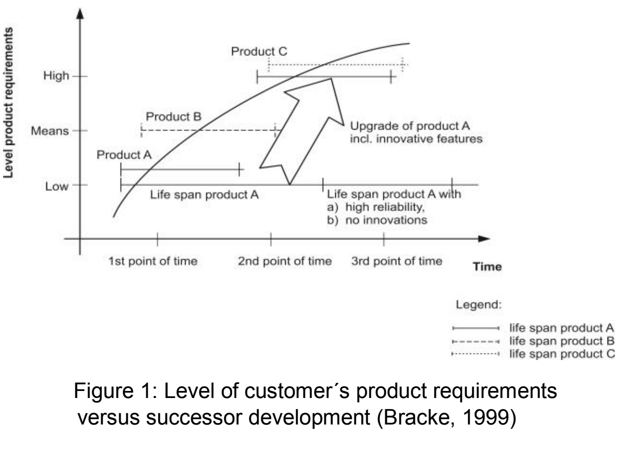


Figure 1: Level of customer´s product requirements versus successor development (Bracke, 1999)

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

Therefore the main question regarding to future environmental products is: What are the influences and interactions of product development, manufacturing and use phase regarding to the focus “Reliable products are sustainable products” of this paper. This paper outlines the “Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept”, substantiated by the automotive case study “clutch”. Based on a typical failure symptom (wearout) of a clutch disk, a method for the linkage of former field damage causes and prospective design phases (design stages) is shown under the boundaries of a long use phase.

2 CDMF-RELSUS-concept: Goals

The focus of this paper is the main thesis “A reliable product is also a sustainable product from the ecological point of view.”

With regard to the substantiation of this thesis, the main pros and cons are as follows:

Pro:

- A reliable product with a long useful life span area saves the following resources: Spare part production, spare part distribution, reuse of components (recycling), disposal of used parts, logistic efforts et cetera.

Con:

- A reliable product with a long useful life span area inhibits cycles of innovation with regard to their functionality and it inhibits clean technology regarding to the interaction with the environment during the use phase.

3 CDMF-RELSUS-concept: Base of operations

3.1 Overview and fundamentals

The “Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept” deals with three iterative points of view to evaluate a product regarding to the thesis “Reliable products are sustainable products”. The three evaluation directions are as follows:

1. Impact of product design:
   Development of reliable products in contrast to product innovation cycles and reparability during use phase.
2. Impact of manufacturing planning:
   Analyse of machines/ facilities/ materials/ suppliers/ material flow during manufacturing (water, electricity, operating fluids, additives etc).
3. Impact of use phase:
   Verification of product reliability in the use phase; allowance of product recycling efforts regarding to the end of product´s life span area.

Before the main impact factors are substantiated in the following subsections, a more detailed overview will be mentioned.

The basic idea of the CDMF-RELSUS concept is the comparison of possible values which can be determined during the manufacturing planning and the use phase to support the decision making during the product life cycle. This assists to find an optimum solution for positioning innovation cycles (e.g. upgradeability) during the product life cycle with regard to the main goals of reliability and sustainability and the boundary conditions of a long use phase. The general process of this concept is shown in Figure 2, which combines on the one hand excerpt of the product life cycle and on the other hand the different innovation cycles (cf. Fig. 1). Each upgrade cycle λ is referred to an assembly i and its grade of upgrade k. Inside one upgrade cycle λ_(i;k) the product design phase deals with a number of assemblies i to z with an amount of components 1 to n. After the assembly is designed, the manufacturer plans the needed assembly, disassembly time and thus the proposed energy consumption for each assembly process i to z. Due to different perspectives, varied sustainability values val_(i;x) can be generated for each assembly process. After the products are delivered, the reliability of each assembly (e.g. component) i to z can be verified by state of the art methods (e.g. Eckel-method [18]) to determine the probability for upcoming defective assemblies val_(i;y). By building a linear or non-linear mathematical function of the values val_(i;x) and val_(i;y) the Relsus_factor_i can be obtained for each assembly.

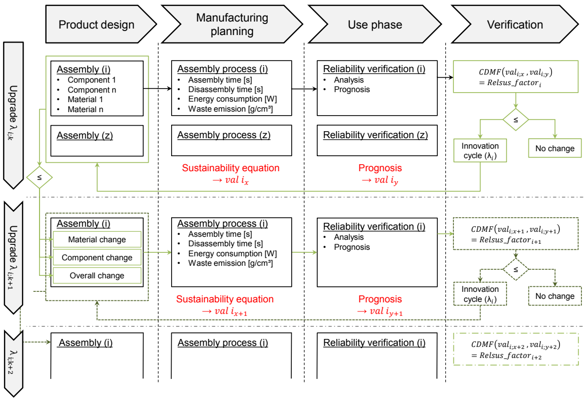


Figure 2: The CDMF-Relsus concept inside the product life cycle

The Relsus_factor_i can be a key element to specify a time-depending area for a strategic upgrade-cycle λ_(i;k+1) or not. If the decision leads to an upgrade-cycle, the former assembly i is renewed inside this cycle. With this significant assembly change by new materials or single components a new value val_(i;x+1) has to be determined in the manufacturing planning process. Afterwards the reliability of the assembly val_(i;y+1) has to be verified again, to examine the accomplished upgrade.

3.2 Assembly strategy optimisation due to innovation cycles (three construction stages)

This study introduces the case study of automotive clutch disk to focus on the innovation cycles. A clutch disk is used in an automotive transmission and is sandwiched in between the flywheel and the pressure plate. Figure A shows the schematic view of the clutch disk. This study focuses on the construction stages of a torsion spring of the clutch disk. There are coil springs located between the splined hub and the friction disc assembly. When the clutch is engaged, the pressure plate jams the friction facing against the spinning flywheel. The torsion springs compress and soften, as the friction facing first begins to turn with the flywheel. Through the movements of the expansion and contraction, the torsion spring absorbs some of the vibration and shock produced by clutch engagement.

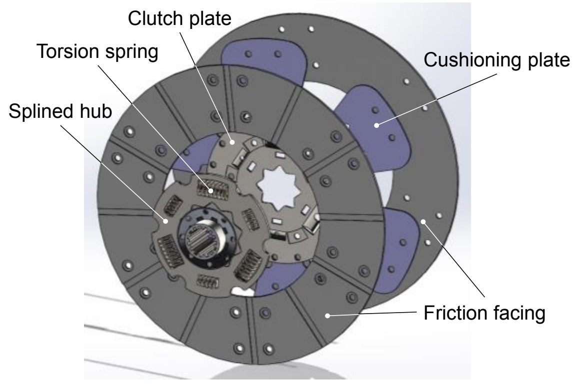


Figure 3: Schematic view of a clutch

The torsion springs are sometimes damaged due to fatigue breakdown. The case study has three construction stages: I, II, and III. The construction stages include the countermeasures such as the redesign of the splined hub and the torsion spring. Details of the improvements are different variants and combinations of materials and component geometries.

3.3 Determination of the assembly´s sustainability values

Automotive and most of their components are assembly products, where each part is assembled to become one product. In automotive manufacturing, it is known that the total number of parts is more than 30,000 items, all parts are gathered by procurement from suppliers in supply chains bridged among suppliers, manufacturers and customers, and their final assembly by a manufacturer is often carried out at assembly line systems (ALS) [13]. The ALS is a traditional production system established as a Ford production, and basically consists of serial production stations connected by conveyors. This system is superior in the efficiency for flow of materials/ units because the work stations are connected by material handlings such as conveyors [8].

Two main economical aspect of the assembly line is assembly time and line balancing [8]. Most of assembly works are still done manually by human operators since the works are complex and should be flexible. The reduction of the assembly time by product design and work improvement contributes to reduce the labour costs. Also, the line balancing is to assign each elemental assembly task to each workstation/ operator with a division of labour, and the balance loss inevitably occurs at the line production. When the line has a good balance, it contributes to reduce the number of and cost of the facilities/ operators.

With regard to sustainability for these assembly products by manufacturing, three environmental issues mainly are: global warming, material circulation and biodiversity [14]. Global warming is the phenomenon by which the world average temperature rises due to the rising concentrations of GHGs, particularly CO2. Materials of each part must put out CO2 by mining, manufacturing and logistics, therefore, the low-carbon supply chain should be constructed, where their CO2 emissions should be visualized and reduced along the entire supply chain because products are manufactured by more than one process or enterprise [14]. By using life cycle inventory data bases, the CO2 volumes of each part can be estimated (for example, [15]).

On the other hand, the material circulation is also required because natural resources such as materials and energy are scarce, and waste becomes more serious. To promote material circulation and reduce the generation of wastes, reuse and recycling should be promoted by closed-loop supply chain [16] which is consisted of regular and reverse supply chains with disassembly [17].

When a more reliable part/ component are introduced for sustainable products, the mentioned economic and environmental aspects are quantitatively evaluated in advance for the whole product lifecycle. Therefore, they are still design challenges how to evaluate the economic and environmental aspects in advance, and how to harmonise the economic and environmental objective by product design and production management after the evaluation.

3.4 Determination and analysis of the assembly´s failure occurrence

A general procedure to verify the reliability of an assembly due to a known failure mode is the analysis of the failure behaviour after a certain usage time and thus the determination of upcoming damaged assemblies by using various prognosis methods. Inside this paper each innovation cycle (e.g. construction stage) has been analysed after six months in service (MIS). Furthermore the prognosis has been evaluated under the usage of the Eckel-method [18].

Figure 4 shows the different analyses due to a changing failure mode of the first to third failure occurrence regarding to the construction stages and manufacturing influences. The first manufactured assemblies lead to a failure rate of ‘X’ % after 6 MIS, whereas the second construction stage leads to much lower failure rate of nearly ‘Y’ %. Furthermore it can be seen that the failure mode itself changed. The highest documented failure occurrence is inside the second construction stage at ‘Z’ km and the failure mode seems now to be dominant at ‘Z2’ km. A main influence on this change between both failure modes can be seen as an assignment of a new material.

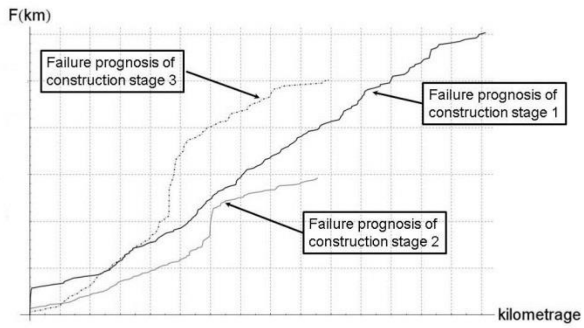


Figure 4: Risk analyses after six months in service of each innovation cycle

The last construction stage which has been analysed shows comparable failure behaviour but leads to higher expected amount of upcoming failure assemblies of nearby ‘Z’ %.

With the given characteristics (material selection, waste pollution and failure rate) the need of a close innovation cycle reflecting all influences should be obtained and is discussed in the following section to verify the methods attempt regarding reliable and sustainable assemblies.

4 VERIFICATION CDMF-RELSUS: APPROACH WITH REGARD TO CASE STUDY CLUTCH

The verification of the iterative CDMF-RELSUS concept is shown inside this paper after the third innovation cycle/ construction stage.

Figure 4 illustrates the given boundaries after the third established innovation cycles. Thus the figure shows the amount of reliable assemblies after 18 month in service, the needed manufacturing energy per assembly and the wasted emissions per assembly in space. In addition a function has been fitted by using a general polynomial of second order to substantiate relationship between the characteristics.

With these given characteristics (e.g. fitted function), various optimisation methods [9] can be obtained to generate a nearby optimal solution between the acceptable failure occurrence and the maximum acceptable investigated energy to still maintain a required critical value of waste pollution, for example.

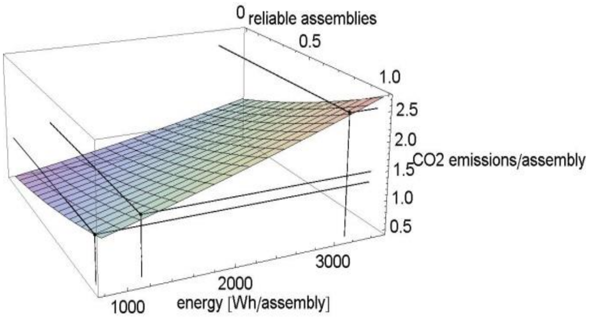


Figure 5: Determination of the Relsus_factor_3 to verify an optimised innovation cycle 4

Inside this paper the transposed characteristics (simulated data and exemplary units) after the third innovation cycle of the clutch disk are shown in Table 1.

Table 1: Simulated data to generate the RELSUS_factor after the third innovation cycle

	Maximum failure occurrence [%]	Energy [Wh]	CO_2 emissions per assembly [g/cm³]
Minimum value		2000	1.011
PV	3.5	2150	1.094
Maximum value		2200	1.123

The maintained critical value of waste pollution should be smaller than 1.1 g/cm³ of CO2. With the given boundaries manufacturing the clutch disk within an amount of 2000 – 2200 Wh and a maximum acceptable failure rate of 3.5 % various possible values of waste pollution that fulfil the requirements (PV) can be calculated.

Therefore the fitted function leads to a possible value of 1.094 g/cm³ if the given failure occurrence of 3.5 % can still be justified by applying an investigated energy of 2150 Wh.

5 CONCLUSION

The “Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept” shows aspects, influences and strategies to substantiate the thesis “A reliable product is also a sustainable product from the ecological point of view.” It shows the complexity and the interdependences of the three main impacts product design, manufacturing planning and use phase. The CDMF-RELSUS concept is a first base of operations for the development of a successor model, which combines the characteristics of sustainability and reliability.

This paper shows a method to combine different values to appraise future decisions to obtain an optimal innovation cycle. Under usage of such a new implemented construction stage the aspects of sustainability and reliability are considered more precise. Methods of the CDMF-RELSUS-concept were demonstrated within the automotive case study “clutch”. Furthermore, an approach for verification of the fundamental CDMF-RELSUS iteration process is shown with regard to three clutch innovation cycles are shown.

Future research work will contain checklists and criterions, which help the design engineer to consider the combination of sustainability and reliability with regard to the product construction and manufacturing. Furthermore, case studies and design examples will be adopted more precise to validate the proposed concept of this paper. Inside future case studies different mathematical functions will be applied to verify the disparity in describing the characteristics relationships.

Based on full CDMF-RELSUS concept and the case study, a guideline will be developed, how to consider verified product reliability based on field data in the successor development. Finally, the CDMF-RELSUS concept considers the interaction of the intended end of the product´s life cycle (product recycling or material recycling) regarding to the environment.

5 REFERENCES

[1] Bracke, S., 1999, Qualitätssicherungsstrategien für die Wiederverwendung von Baueinheiten aus komplexen technischen Investitionsgütern innerhalb eines Produktrecyclings. Book series: Berichte aus dem Maschinenbau, Shaker publisher.

[2] Xing, K. and Belusko, M., 2008, Design for Upgradability Algorithm: Configuring Durable Products for Competitive Reutilization, Journal of Mechanical Design, Vol. 130, Issue 11, pp. 111102.1-111102.14.

[3] Fukushige, S., Arino, M. and Umeda, Y., 2012, Computer-Aided Design for Product Upgradability under Geometric Constraints, Design for Innovative Value Towards a Sustainable Society, Springer, pp. 828-831.

[4] Stadtler, H. and Christoph, K., 2000, Supply Chain Management and Advanced Planning, Springer-Verlag Berlin Heidelberg.

[5] Shapiro, J. F., 2001, Modelling the Supply Chain, DUXBURY, CA, USA.

[6] Yamada, T., 2012, Designs and Challenges in Closed-Loop and Low Carbon Supply Chains for Sustainability, Journal of Information and Management, Vol. 33, No. 1, pp. 94-100, Invited Paper (in Japanese).

[7] Yamada, T., Inoue, M., Ishikawa, H., Yura, K., 2009, A Collaborative Disassembly Evaluation between Product and System Design with PLM, Proceedings of the 7th Global Conference on Sustainable Manufacturing, Sustainable Product Development and Life Cycle Engineering, Chennai, India, Nov., Proceedings and CDROM, pp. 301-306.

[8] Yamada, T., Kakefuda, S., Matsui, M., 2006, Strategic Selection of Assembly Systems under Viable Demands, Assembly Automation, Vol. 26, No. 4, pp. 335-342.

[9] Alt, W., 2002, Nichtlineare Optimierung, Vieweg, Braunschweig

[10] Bracke, S. and Haller, S., 2009, The “field damage analysis” (FDA) - process for supporting the development of environmental-friendly products. Proceedings: 7th Global Conference on Sustainable Manufacturing; Sustainable Product Development and Life Cycle Engineering; Indian Institute Technology Madras, Chennai, Indian.

[11] Bracke, S. and Haller, S., 2010, Advanced Reliability Analysis of Warranty Databases (RAW)’ Concept: Support Sustainable Products and Manufacturing. Proceedings: 8th Global Conference on Sustainable Manufacturing; Architecture for Sustainable Engineering – The UAE Case, In: Advances in Sustainable Manufacturing (Hrsg.: G. Seliger, M. Khraisheh, I. Jawahir), CIRP, Springer publisher.

[12] Celis, M., Dennis, J. E., Tapia, R. A., 1985, A trust region strategy for nonlinear equality constrained optimization, Numerical Optimization (Boggs, P., Byrd, R., Schnabel, R. eds), Philadelphia, SIAM.

[13] Yamada, T. and Matsui, M., 2002, A management design, approach to assembly line systems, International Journal of Production Economics, Vol. 84 No. 1, pp. 99-110.

[14] Takakuwa, S., Son, N. H., Nguyen Dang Minh, N. D. (Eds.), Yamada, T., 2012, Part 6, 6.2, “Design of Closed-loop and Low-carbon Supply Chains for Sustainability”, Manufacturing and Environmental Management, pp.211-221, National Political Publishing House.

[15] Yamada, T., Suzuki, Y., Masui, T., Itsubo, N., Inoue, M., 2012, Disassembly System Design with Environmental and Economic Parts Selection using Life Cycle Inventory Database by Input-Output Tables, 10th Global Conference on Sustainable Manufacturing (GCSM 2012), Istanbul, Turkey, pp.321-326 on CDROM, Oct.

[16] Guide, V., Danile R., 2003, Business Aspects of Closed-Loop Supply Chains. Pittsburgh, PA, USA: Carnegie Mellon Univ. Press.

[17] Gupta, S. M. (Editor), 2013, Reverse Supply Chains: Issues and Analysis, CRC Press.

[18] Eckel, G., 1977, Bestimmung des Anfangsverlaufs der Zuverlässigkeitsfunktion von Automobilteilen. Qualität und Zuverlässigkeit, Vol. 22, Issue 9, pp. 206-208.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

13.2 New approach to integrate customers in early phases of product development processes by using virtual reality

M. Huber[1], J.-P. Nicklas[2], N. Schlüter[2], P. Winzer[2], J. Zülch[1]

[1] Department for Industrial Sales Engineering, Ruhr-University Bochum, Germany

[2] Research Group Product Safety and Quality Engineering, University of Wuppertal, Germany

Abstract

Increasing product complexity, reducing time of product design phases and a rising number of customer requirements impede the product design, especially for small and medium-sized enterprises. In order to solve these problems a new approach for an effective, efficient and sustainable product design by integrating customer demands to reduce time to market and increase resource efficiency has to be developed. Customers and product designers have to get involved in an early stage of the product design process, using a virtual reality environment, to realize an interactive experience of applications, focusing customer demands to generate "tailor-made" solutions. Therefore this paper points out, how virtual reality can be already used in early design phases to communicate with customers. It will be described how product designers and customers can interact. Concerning surveys of determining factors for the different design phases, a general product design process via VR will be illustrated.

Keywords:

Product Development Process, Resource Efficiency, Sustainable Product Design, Virtual Customer integration (VCI), Virtual Reality (VR)

1 INTRODUCTION

Fuzzy Front End of innovation, ambiguous projects as well as vague product demands are factors that lengthen time to market. A study on time-consuming factors [1] defines two as significant: unclear project goals at the beginning of a project and changing project specifications. Costs and quality, resource efficiency, and (process) effectiveness determine the challenges for producers as well as developers. They build the adjustments for sustainable product development. Due to these facts, increasing product complexity, demands of contracted product development processes, and a rising number of customer requirements characterize the present market situation. In particular, small and medium-sized enterprises' (SMEs) main focus has to be speed and flexibility to face these challenges and to survive in the global market [2, 3]. A sustainable product development process, by integrating customer demands as the important variable in the early stages of product development, seems to be the competitive advantage to differentiate between one's own business and the competition. As the success of a product is largely decided during its early development phases, the use of the customer demands as well as knowledge of the product itself should be continuously integrated into the early product development processes. Therefore, to reduce uncertainty in the product development processes as well, customer preferences and needs have to be gathered in the early phases [4]. Furthermore, costs of product modification are determined more precisely if the requirements and the product functions are known at an early stageas well as avoiding expensive redesigns or unsatisfactory products (cf. figure 1). Rising modification costs can be minimized by an increased product knowledge (characteristics in figure 1). The problem to be solved is the determination of requirements and related product functions. Already existing methods in this context are expert interviews, lead-user analysis, and market surveys. Nevertheless the integration of customers in the early phases of the product development is still not satisfying. Therefore, the idea of using new technology such as Virtual Reality (VR) for costomer integration is getting more and more important [5].

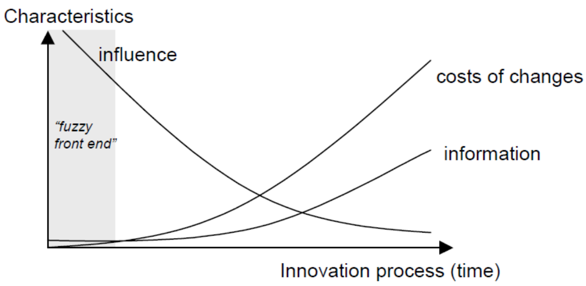


Figure 1: Influence, cost of changes, and information during the innovation process taken from [6].

It is proven that VR-environments offer the chance to review virtual prototypes in the early stages of product development processes [7]. In a next phase, the possibility of integrating the customer in the virtual product development processes has to be explored. Discipline-specific as well as customer-specific demands can be concretized into requirements. The fulfillment of these requirements can be tested. For this reason, a user-centric or customer-centric product development process with integrated VR processes is needed.

Corresponding to the above-mentioned facts, this paper points out how VR can be used in early product development processes in order to communicate with customers and integrate customer requirements. Therefore, the product

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

development processes are standardized and analyzed for VR-usage. It describes the possibility of interactions between product designers and customers and enables the product designer to carry out a survey of determining factors. A systematic customer confrontation with product designers in an early stage on the product development process in a VR-environment realizes an interactive experience of applications, associated with highly visual, immersive 3D environments in order to elicit customer demands in an application-oriented context. This kind of customer integration, focusing on the expressions of customer's or rather user demands on a common basis, helps product designers to generate "tailor-made" solutions. Aquired requirements and specified product information are integrated into the product development process via continuous customer integrated VR-usage.

The new approach of integrating customers in VR development processes for a successful and innovative product development is based on a generalized product development process that includes VR-usage.

2 PRODUCT DEVELOPMENT PROCESS

The product idea, as the first result of a product development process, must achieve target market needs through the consiceration of strategic positioning and a vague, but innovative, product idea. During the generation of the product idea, information from market research and ideas of the SMEs have to be united. Moreover, identifying, gathering, and defining product requirements from the Voice of the Customer [8], during this phase of product development, is a main goal of the newer product development literature. At this point, the relevant literature is taken into account to illustrate a general product development process: English literature dealing with New Product Development and German literature refering to the relevance regarding practical application (e.g. [9, 10, 11]). A verification of SMEs on the basis of this literature analysis was carried out. This analysis can be summarized as following: the different standardized development processes show a lot of parallelisms; The only differences in the level of abstraction are due to the detailed sub-processes. In a broader sense, sustainable product development is manifested in effective and efficient product development processes.

The following generalized product development process (cf. figure 2) is based on the analyzed literature and is relevant to practical application. It was also peer-reviewed by SMEs integrated in the German research project VitAmIn (**Vi**r**t**uelles **A**nforderungs**m**anagement im kundenintegrierten **In**novationsprozess) [12]. Its abstraction to four process phases on the highest process level guarantees validity for different fields of application in product development as it is introduced in [11]. The four phases - named by their output - are "product idea", "product concept", "product", and "market launch." In the second level - the first level of sub-phases - eight phases represent a more detailed product development process. "Strategic positioning" is the starting point, followed by "idea generation" and the gathering of "product requirements." The "Concept development" and "product development" are followed by "product testing." The phases "production planning" and "commercialization" represent the phase market launch.

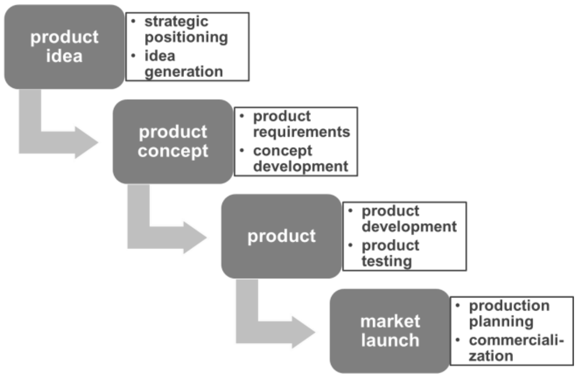


Figure 2: Generalized product development process (in particular following [11]).

The generalized product development process shown above provides an overview of the different kinds of phases and offers a unique characterization. In order to gain customer demands at an early stage of product development those early phases have to be taken into consideration, which offer the possibility to gather holistic requirements, market needs, and customer demands. Which phases offer the chance to use VR and to integrate customershas to be figured out. Both VR and customer integration have to be compared with their potential of usage for the different product development process phases.

3 CUSTOMER INTEGRATION

Today, the process of capturing preferences and expectations, well known as the Voice of the Customer (VOC), is one of the companies' strategies or focus. Customers and their opinion are becoming more and more important for companies. That is why customers are no longer seen as users, but as partners. This new role of customers and a closer cooperation between customers and companies involve benefit for both sides, i.e., companies generate improved products and have lower risks and customers have the opportunity to announce their demands in order to increase their fulfillment. To use the customer knowledge effectively, companies have to integrate their customers over the product-lifecycle [13] i.e., with the help of modern information and communication media that offers the possibility to gather customer knowledge and allows the innovative integration of this information into the early phases of the product development processes [14]. This customer integration is discussed in literature and has increasing attention in businesses [15]. It is also a critical factor for both the success of the company and the new product [16, 17]. Already 75% of SMEs think that customer participation is a significant success factor to raise innovative capability and 90% take customer feedback into account for an important performance criterion [18]. Consequently companies have to incorporate customer experiences [19]. Right now, the research methods for Virtual Customer Integration (VCI) are in favor of improving product development [15] and hold a key position in connecting to the required customer integration with virtual tools in the "product testing" and "production planning" phases.

It was already proven that the methodological approaches of "standard" customer integration can be used in the generalized product development process of newer product development literature. The use of VR for VCI is also tested in several industries, primarily in the automobile industry in later development processes. The reason for this late application is that VR and customer integration are not yet combined. Since the methodological concepts are not influenced by an early customer integration, the usage of the above-mentioned concept is given.

The reason for using VR only in the later development processes is the supply of data and CAD models for the VR. Which early phases of product development processes are linkable with VR has to be figured out in order to use VCI in the early phases of product development. It has to be analyzed, at which point the information and data of the product idea is sufficient to use in VR. Therefore, the requirements of VR and the data outputs of early phases of product development processes are compared in the following paragraph.

4 VIRTUAL REALITY (VR)

VR realizes computer-simulated products and their application in different environments. Primarily, VR is used for visual experiences, realized through stereoscopic displays. At present, companies use VR for product presentation to underline product functions and to influence the decision-making process (cf. figure 2: market launch). Additionally, it is used for product configuration which assumes that the product components are nearly developed to a final level. Comparable to Digital MockUps (DMUs) or physical prototypes, VR is used in late phases of product development processes. Furthermore, VR is used in the digital production, for example for assembly-planning [20]. Moreover, many different VR-software solutions are offered to enable collaborative work of globally distributed development-teams. Consequently, there are many VR-systems in use. Within the project VitAmIn, a new VR-system called IEL (Immersive Engineering Lab) of the Fraunhofer IAO is used. This system enables personal immersion (PI). Currently, the IEL of Fraunhofer IAO represents the state of the art in VR-systems.

In practice, VR is used in late phases of product development processes (e.g., market launch). The main reason for this is the need of product data in form of CAD. In SMEs the modeling of a product by CAD is often scheduled in later phases of the product development where all requirements and functions of the product have already been determined.

But as a matter of fact, there are sufficient product data in earlier phases, also in CAD, to run a VR-session. These data are an assembly of excerpts, outlining specific product functions or innovative ideas. Although these data are not enough for a complete CAD-model of the product with all its functions and components, it can be used in VR to visualize the product ideas and innovative aspects.

5 NEW APPROACH

Virtual customer integration via VR in early phases of the product development process builds the challenge for successful product innovation and simultaneously represents the new approach of VR development processes in future.

As above mentioned, there are the following demands to be taken into consideration:

- The theory of newer product development processes with the focus on market needs
- Customer integration through strategies like VOC and VCI
- VR as a virtual development method on the basis of CAD-data.

As there is a need for CAD-data in order to run a VR-session this is the main focus during the product development process analysis. To realize virtual products for customer integration, the following figure shows possible starting points for VR in the early phases of a generalized product development process. The focus is on the early phases (cf. chapter 2), however VR should also be used in later product development process phases as mentioned above.

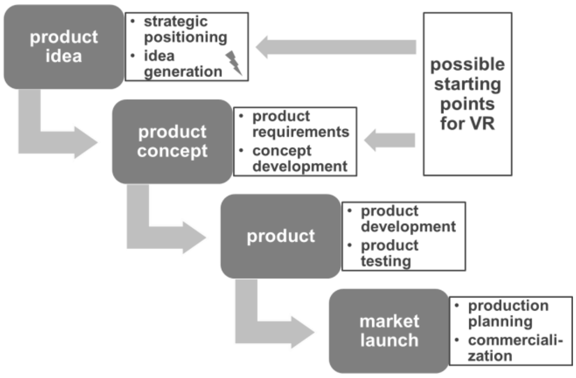


Figure 3: Possible starting points for VR in early phases of a generalized product development process.

The marked phases (product idea and product concept) are suitable for VR-involvement based on the above derived demands. First of all idea generation, including market analysis, represents a significant phase to introduce for example lead-user via VR into product development. In this phase a customer or user confrontation is creative and indefinite (intangible). Immersion in VR can stimulate customer imagination and visions. For example there is the chance to either use predecessor products in a feedback function and/or in contrast to that products that are over-engineered as shown in figure 4. The necessary CAD-data is available and does not represent the new product – the used input information only stimulates the phase of idea generation. The visualization in the following figure represents the rough idea of VR-use in this early phase of the product development process.

Secondly product requirements have to be identified. In a more tangible context product designers and users can concretize requirements in a VR-environment with a virtual prototype characterized by explicit ideas. Information can be gathered and requirements can be weighted by lead-users, focus-groups, or consultation with experts. Therefore only CAD-data on a low level are necessary to build a common basis. A more concrete gathering of ideas and weighting of requirements is on focus. The idea of customer integration into the phase "product concept" is possible.

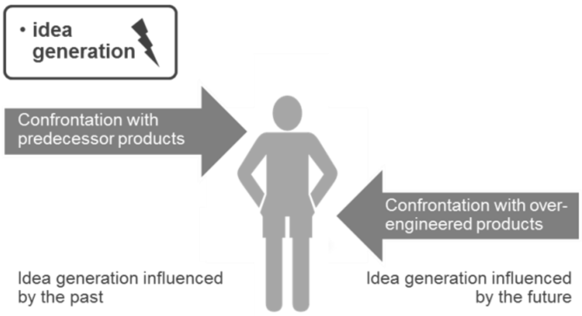


Figure 4: Idea generation in a VR-environment with different incentives.

Customer integration into other phases of the product development process is of relevance as well, for example "product testing." However this is not focused in this paper, since testing a prototype is a late phase in the product development process.

6 CONCLUSION

This new approach offers the possibility to identify the customer requirements continuously and their degree of fulfillment by product functions and/or components to create a more sustainable product developmentSince product development processes are iterative the use of VR as a customer integrating concept should be used at several phases in the whole product development process, introduced in figure 2 [21, 22]. The classical engineering approach of requirements as input into the development stages of product development, and the verification process of the requirement fulfillment are given by gathering, understanding, and articulating the needs of customers by Virtual Customer Integration.

As the use of CAD software tools for product modeling, like DOORS or Requisite Pro, increases in industries characterized by high complexity and dynamic [23], the needed data for VR-sessions are available even in the early phases of the product development processes. Furthermore, the identification of requirements in an interdisciplinary environment of product development seems to be practical [24, 25]. The request of customer integration into an early phase of development processes is present [26]. Virtual engineering methods seem to be adequate to build the solution for diametrical descriptions of requirements [9, 27] that are solution-neutral (product designer) or solution-oriented and intuitive (customer).

VR offers the chance to communicate on a common basis and helps to clear up misunderstandings. Product designers and users can be confronted systematically and can discuss ideas or problems. Furthermore, the firm's knowledge base for a new product development can be improved.

The advantages, for example time and cost savings in product development, can be achieved by replacing physical prototypes by digital simulations in all phases of the product development process. Therefore, the acceptance of VR-simulation has to be firmly established. Over time, technical limitations have to be overcome to create a high-fidelity VR-experience.

Further research, regarding the process of VR-use and in connection with this the integration of VR into the product development process, has to be done.The focus is the gaining of reliable and significant evidence that the use of VR reduces costs in early phases of product development. Furthermore, key points and methods have to be standardized to implement VR as a continuously used tool in product development processes for VCI to implement the Voice of the Customer. These problems will be considered in further works of the project VitAmIn.

7 REFERENCES

[1] Kirner, E., Dreher, C., Maloca, S., 2006, Möglichkeit zur Innovationsbeschleunigung aus Sicht der Unternehmen. In Bullinger, H.-J. (ed.): Fokus Innovation, pp. 137-157, Hanser, München.

[2] Scharn, R., 2006, Das strategische Verhalten von kmU. In Winzer, P. (ed.): Generic-Management und Möglichkeiten der Stakeholderintegration. Shaker, Aachen.

[3] Sitte, J., Winzer, P., 2011, Demand Compliant Design. In IEEE Transactions on Systems, Man and Cybernetics, Part A, Volume 41, pp. 434-448.

[4] Ernst, H., 2002, Success factors of new product development, a review of the empirical literature. In International Journal of Management Reviews, Vol. 4 (1), pp. 1-40.

[5] Bartl, M., Füller, J., Mühlbacher, H., Ernst, H., 2012, A Manager´s Perspective on Virtual Customer Integration for New Product Development. In J PROD INNOV MANAG 2012, Product Development & Management Asiciation.

[6] Herstatt, C., Verworn, B., 2001, The „Fuzzy Front End" of Innovation, Working Paper No. 4.

[7] AVL GmbH (ed.), 2013, Virtuelle Produktentwicklung, Vol. 1, Vogel Business Media, Würzburg.

[8] Campos, J, Balland, JC, 2012, The Voice of the Customer for Product Development. 4th Edition, Rapidinnovation.

[9] Pahl, G., Beitz, W., Feldhusen, J., Grote, K. H., 2006, Konstruktionslehre. Grundlagen erfolgreicher Produktentwicklung. Methoden und Anwendung. Vol. 7., Springer, Berlin.

[10] Ehrlenspiel, K., 2009, Integriertie Produktentwicklung, Denkabläufe, Methodeneinsatz, Zusammenarbeit. Vol. 4., Hanser, München.

[11] Spath, D., Dill, C., Scharer, M., 2000, Unterstützung der Produktentstehung mit einem prozessbegleitenden Methodenbaukasten auf Intra/Internetbasis in VDI Berichte 1558, Erfolgreiche Produktentwicklung. VDI, Düsseldorf.

[12] www.projektvitamin.de, (last access 22.04.2013).

[13] Rautenhaus, S., 2007, Kunden an der Unternehmensspitze. In QZ (52), No.1, pp. 31-33.

[14] Zäh, M. F., Wagner, W., 2003, Factory Planning Modules for Knowledge Sharing Between Different Locations. In, Zülch, G., Stowasser, S., Jagdev, H. S. (eds.), Proceedings of the IFIP WG 5.7 Working

Conference on Human Aspects in Production Management, Vol. 2., pp. 145-151, Karlsruhe.

[15] Hemetsberger, A., Godula, G., 2007, Integrating Expert Customers in New Product Development in Industrial Business – Virtual Routes to Success. Innovative Marketing, Vol. 3, Issue 3, pp. 28-39.

[16] Singh, S., Ranchhod A., 2004, Market orientation and customer satisfaction, Evidence from British machine tool industry. In, Industrial Marketing Management, Vol. 33 (2), pp. 135-144.

[17] Kahn, K. B., 2001, Market orientation, interdepartmental integration, and product development performance. In Jounal of Product Innovation Management, Vol 18 (5), pp. 314-323.

[18] Kirner, E., Maloca, S., Rogowski, T, et. al., 2006, Kritische Erfolgsfaktoren zur Steigerung der Innovationsfähigkeit – Empirische Studie bei produzierenden kmU. Fraunhofer Informationszentrum Raum und Bau (IRB), Stuttgart.

[19] Prahalad, C.K., Rameswamy, V., 2000, Co-opting Customer Competence. In Harvard Business Review, pp. 79-87.

[20] Dangelmaier, W., Lentes, J, Döring, A., 2009, New production strategies for automotive industries. In Automobiltechnische Zeitschrift, ATZ-Produktion, vol. 2 (2), pp. 2-5.

[21] Crostack, H. A., Hompel, M. ten, (eds.), 2007, Forderungsgerechte Auslegung von intralogistischen Systemen. Logistics on Demand. 1. Kolloquium am 20. Februar 2007, Sonderforschungsbereich 768, http://www.sfb768.tum.de.

[22] Winzer, Petra (ed.), 2012, PromeSys - Abschlussbericht im Rahmen des Verbundforschungsprojektes „Prozesskettenorientiertes Regelkreismodell für ein nachhaltiges robustes Design mechatronischer Systeme“. Vol. 1, Shaker, Aachen.

[23] Hood, C., 2005, iX-Studie zum Thema Anforderungsmanagement. Heise-Zeitschriften, Hannover.

[24] Jung, C., 2006, Anforderungsklärung in interdisziplinärer Entwicklungsumgebung. Techn. Univ. München.

[25] Schmidt, R., 2007, Qualitätsgerechte Entwicklung softwareintensiver technischer Systeme. Shaker, Aachen.

[26] Holzmüller, H.H., Jockisch, M., Matijevic, M., 2007, Herausforderung bei der Erhebung von Kundenanforderungen an intralogistische Systeme. In Crostack, H.-A., ten Hompel, M. (eds), Forderungsgerechte Auslegung von intralogistischen Systemen – Logistics on Demand. 1. Kolloquium am 20. Februar 2007, Sonderforschungsbereich 768, http://www.sfb768.tum.de.

[27] VDI 2206, 2004, Entwicklungsmethodik für mechatronische Systeme. Beuth, Berlin.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

13.3 How to solve the new product design model considered life cycle cost and product architectures

Ikou Kaku[1], Dongxiao Jiang[2], Renqian Zhang[3], Yong Yin[4]
[1] Department of Environmental Management, Tokyo City University, Japan
[2] Department of Management Science and Engineering, Akita Prefectural University, Japan
[3] School of Economics and Management, Beihang University, China
[4] Faculty of Literature and Social Sciences, Yamagata University, Japan

Abstract
A novel product design model is proposed in order to develop a new product in terms of global performance by using a Boolean quadratic model, where the relationships among functions and interfaces are illustrated by using life cycle approach. Considering integrity, for example, can be presented as a good design in which the disassembly and recycle of the product will be performed easily. This concept can be used to illustrate and modify the proposed model. However because solving the proposed quadratic model is hard, we transfer it to a simple linear programming form without changing its identical feature. Then a branch and bound algorithm is proposed to solve the linear programming transformation model. Numerical experiments are provided to show the effectiveness and efficiency of the algorithm. As a result, optimal solution of a 16-devices case (nearby real world) can be obtained in a reasonable computation loads.
Keywords: Product architecture; Product development; Integrality; Modularity; Life cycle approach; Combinatorial model; linear programming transformation, Branch and bound algorithm

1 INTRODUCTION

At the 10th Global Conference on sustainable Manufacturing (GCSM2012), we have proposed a novel product design model in order to develop a new product in terms of global performance by using a Boolean quadratic model, where the relationships among functions and interfaces are illustrated by using life cycle approach [1]. To cooperate integrity into new product had been recognized being very important in product design process ([2] [3] [4]). We have introduced the life cycle costing method to combine integrity and modularity into an interface, which connecting functional components to achieve global performance. Also an explanation on the relationship between product complexity and life cycle cost has been given, and a quadratic combinational optimization model has been presented. However, only simple examples were shown in the proposal therefore it is not enough to show the mind and complexity of the proposed model. In this paper, after illustrating the calculation complexity of the model, we transfer the model to a simple linear programming form without changing its identical feature. Then a branch and bound algorithm is used to solve the linear programming transformation model. Examples are used to show the effect and utility of the solution method.

The paper is organized as follows. Section 2 provides an overview on life cycle cost and product architecture, and defines the integrity with lifecycle cost. Section 3 explains how to model the design process. Section 4 presents the linear programming transformation and describes the parameter used to constraint the variables. Section 5 presents the algorithm of branch and bound method. Section 6 shows the calculation examples, and discusses the calculated results. Finally, section 7 presents our conclusions.

2 OVERVIEW ON LIFE CYCLE COST AND PRODUCT ARCHITECTURE

2.1 Life cycle cost

Life cycle is usually divided from an individual product's perspective into three or four steps. Fabrycky & Blanchard (1991) [5] used a four-step division to categorize the costs of an individual product: (i) Research and development cost; (ii) Production and construction cost; (iii) Operation and maintenance support cost; and (iv) Retirement and disposal cost. Hence, life cycle cost can be presented as follows.

$$C_{LCC} = C_D + C_M + C_U + C_R \qquad (1)$$

where,

C_{LCC}: total life cycle cost

C_D: development or design cost

C_M: production or manufacturing cost

C_U: usage and maintenance cost

C_R: retirement and disposal cost

Several methods for estimating the life cycle cost had been introduced in [5]. By using the engineering procedures method those costs are assigned to each component at the lowest level of design detail and then combined into a total for the product. This method might result in an accurate estimate if all the needed data is available and the estimator doesn't cut any corners.

Despite this formal categorization, life cycle cost has been criticized for lack of consideration of design costs [6]. One of

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

our purposes in this paper is to overcome such shortcoming and to use these costs to evaluate the system performance of a design process. It is considerable that life cycle costs are influenced each other. For example, designing a product with higher decomposability might increase C_D but decrease C_R. Good cases in real world can be found from Japanese automobile industry because a lot of parts of car are redesigned for easy reuse and remanufacturing in past decade. Therefore, how to design functions and interfaces in which life cycle costs are considered in trade-off relationships is a very interesting decision problem in design for environment.

2.2 Modularity and integrity

For designing a product in life cycle through architectures, we should re-clarify following concepts of function, interface, modular and integral, and explain the relationships among them according to life cycle costs.

A product is defined as a device that performs a variety of functions that would otherwise be carried out by separate single function devices. In a modular architecture, the mapping from functional elements to physical components is one to one, i.e., one functional component only maps one physical component where functional component (or component) is the smallest unit of a decomposable product. Even sometimes the functions (components) also are designed integrally, it is not frequent because functions (components) are required by market and cannot be ignored. Interfaces (interactions) are between system functional components to support the system functions, which may be related to and evaluated with several criteria like as energy, materials, information and space [6]. Most components of a modular product are interchangeable and the interfaces are standardized. On the other hand in an integral architecture, the mapping from functional elements to physical components is not one to one and the interfaces among interacting physical components are not often standardized. Product with integral architecture refers to the consistency between a product's function and its structure: the parts fit smoothly; the components match and work well together; the layout maximizes available space. For an integral product, a change in some functional elements or component will lead a change to other components in order for the overall product to work correctly.

It should be noticed that designing an interface not only just have two ways, i.e., modular or integral. Even in a modular design, some integral thinking may be used, and vice versa. Several examples can be found in Toyoda's Home Page [7], one of them is scrapping of bumper, which is a component of a car, and is designed to fix it forth and back of a car to prevent accident. Figures 1 and 2 are shown to illustrate the improvement of scrap techniques of bumper. By redesigning the scrap process (includes configuration, materials, jogs and some other techniques), the performance of bumper scrap has been improved remarkably (90% cost down and saves about half time of operations). Therefore, it is reasonable to consider that the modularity and integrity may coexist within a product even within an interface. It shows that, an interface can be designed based on a modular architecture, and increasing integrity by redesigning its energy, materials, information and space (so-called global performance [8]) can be achieved. If we want to evaluate the global performance by life cycle cost then how does the integrity (or modularity) influence the lifecycle cost?

As pointed out in above example, Figure 1 shows that the design of bumper scrap is standard but does not consider its dismantling after usage. That may lead to a result of high retirement cost, whereas Figure 2 shows a new design considering scrap process. It is clear that the cost of new design is higher than the old because it is based on old design and adds some new ideas to improve the scrap operation, for example, to design new configuration, to use new materials and to design new jogs. It is considerable that to introduce integrity into an interface is not an easy task, and the more the integrity to consider, the more the difficult of the design. That means the design cost may be monotonic increasing with the integrity. Additionally, the new design considered some integrity may lead to several changes in manufacturing but it belongs to fixed cost and very small for a lot of product. Moreover, it should not influence customer usage either. Thus, the manufacturing cost and usage cost are changed very minutely and can be ignored when integrity is designed into an interface. However, if an interface is designed easily to scrap then the retirement cost may be reduced, and the more the integrity to consider, the more the efficient of scrap operations. Hence, the retirement cost may be monotonic decreasing with the integrity.

Figure 1 Before redesign of bumper scrap operations

Figure 2 After redesign of bumper scrap operations (Japanese in the figure means hook, a new design of dismantling tool)

Summarily, it is considerable that even manufacturing cost and usage cost account for most life cycle cost (over 80%) but they are not changing with the ratio of integrity. So that the manufacturing and usage cost can be ignored if we consider the relationship between product architecture and life cycle cost. Moreover, there is a trade off with design cost and retirement cost when the rate of integrity increasing. That means there exists an optimal rate of integrity to minimum total life cycle cost for each interface. And it is considerable that the optimal rate of integrity may is not a value but in a range, depends on what the function of life cycle cost.

2.3 Definition of integrity with life cycle costs

As mentioned above, an interface can be designed with modular, integral and hybrid architecture. The interface may have lower design cost but higher recycle cost if the rate of integrity is low, whereas it may have higher design cost but lower recycle cost the rate of integrity is high. Because the manufacturing cost and usage cost do not influence the optimal value of integrity, here we just consider the effect (cost) of an interface can be presented as below.

$$C = \min\{C_D + C_R\} \quad (2)$$

where, C is the optimal value balanced by design cost and recycle cost of an interface. C_D and C_R are the cost functions of design and recycle, which can be defined as any type but have a trade-off relationship.

Once the system functional components and their relationships are obtained, the number of interfaces (N) can be defined as below.

$$M - 1 \le N \le \frac{M(M-1)}{2} \quad (3)$$

where *M* is the number of functional components. Formula (3) means once functional components are identified there are several different ways to connect them by different interfaces. For example, a product has three functional components, we can use different two interfaces to connect them, or use three interfaces to connect them. Also it is able to consider that there is no any interface between components then the left side of formula (3) is not a necessary one.

It is clear that different interfaces connecting the components may have different performance from formula (2). Designing interfaces in a product can be proposed as an assignment problem in which select interfaces to minimum total life cycle costs. However as discussed above, increasing the integrity in an interface may influence other interfaces and functions so that the total life cycle costs may be changed. i.e., once an interface is selected it may influence other interface will be selected. For example, an interface may be designed as a modular one but it makes other interface easy to design as an integral one, then total costs may be reduced by this selection. Simply in this paper we define such relationship between interfaces as a differential value of their costs as below.

$$\Delta C_{ij} = Def(C_i, C_j) \quad (4)$$

where *i* and *j* are different interfaces and C_i , C_j are the optimal values of the interfaces.

It should be noticed that formula (4) needs a detail discussion because at least two problems existed in formula (4). One is the cost may not be a scalar then how to calculate them should be defined carefully; the other is formula (4) only consider every two interfaces pair but such influence may incurred among all of interfaces. It is also a future research work. By using the concepts defined above, we can model the design process through architectures.

3 MODELING DESIGN PROCESS

Suppose there is a product with *M* functional components is needed to design. Then there may are *N* interfaces exist. How many interfaces should be considered? Which interface should be connected with which interface? Among them how many interfaces are integral? As discussed above, an interface may bring different life cycle cost, and whether it in integral architecture is depended on the trade-off of its costs. Then once an interface is taken into account we can confirm it is whether integral or modular or hybrid. Moreover, whether an interface is taken into account is not only depended on itself but also should consider its influence to other interfaces. Additionally, when a new functional component is contained into the product, which and how many existent components should be connected with it can be modeled, i.e., by using the life cycle cost of itself and calculate the influence that it may give to other interface then we can conclude it into whole product. That means global performance [8] (here is the total life cycle cost) can be achieved by integrate several interfaces into the product, and when a new component is introduced into the product not only new but also old interfaces should be re-revaluated.

Suppose i, j = 1,2,…*N* present interfaces, where *N* is depended on formula (3). The decision variable is defined as follows:

$$x_i = \begin{cases} 1 & \text{int}\,face \quad i \quad exsit \\ 0 & otherwise \end{cases} \quad (5)$$

By using variable x_i the total cost can be presented as follows:

$$TLCC = \sum_i C_i x_i \quad \rightarrow \min \quad (6)$$

Note formula (6) states the situation in where a component only has one interface (in fact formula (6) concludes this fact and as a result several interfaces might be related to a component however these interfaces are considered independently). It is not true in many cases in where a component is able to have several interfaces and these interfaces are related with some reasonable devices. Consider it may influence other existent interfaces if a new interface is taken into a product, say reversely, the cost of taking it into the product is not only from itself, but also from those interfaces which may influence it, the cost of interface *i* should be considered as follows:

$$RC_i = C_i + \sum_{j \ne i} \Delta C_{ij} x_j \quad (7)$$

where ΔC_{ij} is a coefficient defined in formula (4) which shows the influence from interface *j* if it exist. Then we can redefine the model as below.

$$TLCC(X) = \sum_i RC_i x_i = \sum_i (C_i x_i + \sum_{j \ne i} \Delta C_{ij} x_i x_j) \rightarrow \min \quad (8)$$

S.t.

$$\sum_{i=1}^{N} x_i \le a \quad (9)$$

$$x_i, x_j = \{1,0\} \quad (10)$$

Where a is a parameter defined by requirements of design and manufacture. It can be considered that all of the interfaces may exist but each interface only can be influenced by almost a-1 interfaces. i.e., $a \le N$. When an interface is taken into the product (i.e., $x_i = 1$) it may have its own cost C_i. What's more, it also brings some additional cost that influenced by other interfaces (i.e., $\sum_{j \ne i} \Delta C_j x_j$). It can be considered that integrate an interface that may influence many other interfaces, the more interfaces related with it, the higher the integrity can be obtained. Therefore, formula (8) presents the global system performance of life cycle.

Because x_i is a binary variable, its calculation is ordered by 2^N. And once x_i is fixed, x_j is calculated by other interfaces differed to x_i, its calculation is ordered by 2^{N-1}. Then total calculation is ordered by O(2^N). Moreover, because $\{\Delta C_{ij}\}$ is not non-negative definite, it is not able to guarantee that the solution is optimal by using traditional gradient method.

4 A LINEAR PROGRAMMING TRANSFORMATION OF THE MODEL

Consider there exists a special relationship between variable x_i and x_j, in this paper we propose a new variable y_{ij}, which is bounded by x_i and x_j, to change off with the quadratic term $x_i x_j$ therefore transfer the quadratic combinational optimization model to a linear programming form. It is important to harmonize y_{ij} with $x_i x_j$ to guarantee the feature of the model has not been changed.

The following inequality is introduced to present the relationship of y_{ij} with $x_i x_j$.

$$\alpha(x_i + x_j) + \beta \le y_{ij} \le \alpha'(x_i + x_j) + \beta' \qquad (11)$$

Note that x_i and x_j are both 0-1 variables. Thus, if we can set parameters ($\alpha, \beta, \alpha', \beta'$) rationally, inequality (11) can determine the relationship of y_{ij} with $x_i x_j$ uniquely. It can be observed that the inequality is,

(1) If $x_i = x_j = 1$,then $2\alpha + \beta \le y_{ij} \le 2\alpha' + \beta'$.

(2) If $x_i = 1, x_j = 0$ or $x_i = 0, x_j = 1$, then $\alpha + \beta \le y_{ij} \le \alpha' + \beta'$

(3)If $x_i = x_j = 0$, then $\beta \le y_{ij} \le \beta'$.

The parameters $\alpha, \beta, \alpha', \beta'$ should satisfy above three conditions simultaneously to guarantee $y_{ij} = x_i x_j$. Their domain of definition can be shown in Figure 3, where the domain is shown by diagonal line.

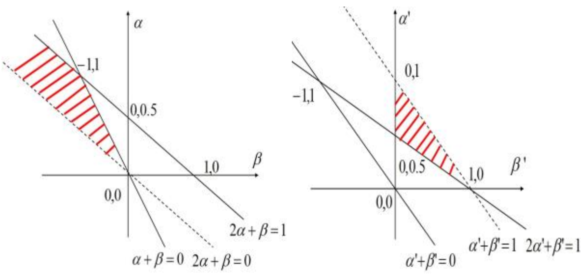


Figure 3 the domain of parameters $\alpha, \beta, \alpha', \beta'$

By using inequality (11) we can transfer the quadratic model to a simple linear programming form without changing its identical feature.

$$TLCC(X,Y) = \sum_i C_i x_i + \sum_{i=1} \sum_{j=i+1} \Delta C_{ij} y_{ij} \rightarrow \min \qquad (12)$$

S.t.

$$\sum_{i=1}^{N} x_i \le a \qquad (13)$$

$$\alpha(x_i + x_j) + \beta \le y_{ij} \le \alpha'(x_i + x_j) + \beta' \qquad (14)$$

$$x_i, x_j = \{0,1\} \qquad (15)$$

$$y_{ij} = \{0,1\} \qquad (16)$$

where formula (13), (16), (18) states the transformation. Note, the variable y_{ij} is a two dimension variable, it may take more calculation time to solve it. The total calculation is also ordered by O(2^N). However, y_{ij} is stated by $x_i x_j$, so efficient method can be used to solve the linear problem.

5 A B&B ALGORITHM FOR SOLVING THE LINEAR MODEL

In this section, we develop a branch and bound algorithm to solve the linear programming transformed model. Branch and bound method is well known for solving 0-1 integer programming problem. Its basic consideration is to separate the primary problem into several sub-problems (usually divide the primary problem in two sub-problems), which called branch. Then relax the sub-problem by withdraw the 0-1 constraint and solve the relaxed problem to get a lower bound, find a feasible solution is near the lower bound as a upper bound, finally obtain the nearest feasible solution as a optimal solution. Based on the consideration of branch and bound method, we can define the operation of branch and bound as bellows.

Branch operation: branch from the first variable of x_i which is not integer in a rise order. i.e., set this non integer variable into 0 or 1.

Bound operation: relax and solve the branched sub-problems by using a well-known interior point method. If all of the variables of the solution are integer then it is the optimal solution. Otherwise it is a lower bound. We can random set x_i and calculate its TLCC as an initial upper bound. If x_i is not satisfying the constraints (formula (13 and (14)) or its solution is larger than upper bound then stop the separation from the point.

The branch and bound algorithm then can be proposed as bellows. We use a simple example with 4 functional components and 6 interfaces to illustrate the algorithm. The search process is shown in Figure 6. Where $[-88.6, -69]^{0}$ shows the $[\text{lower bound, upper bound}]^{\text{number of sub-solution}}$, ○ : Sub-solution whose lower bound (relaxed value) is larger than upper bound, ◎ : Feasible solution, and ⊗: infeasible solution.

Here

C_i = 0.0, 0.0, 0.0, 0.0, -16.0, -5.0

and

ΔC_{ij} =0.0, 0.0, -2.0, 16.0, 10.0, -20.0

0.0, 0.0, -2.0, -14.0, -8.0, 12.0

0.0, 0.0, 0.0, 6.0, -6.0, -12.0

0.0, 0.0, 0.0, 0.0, 20.0, 16.0

0.0, 0.0, 0.0, 0.0, 0.0, -18.0

0.0, 0.0, 0.0, 0.0, 0.0, 0.0

are generated randomly, and set the parameters $\alpha = \alpha' = 0.5, \beta = -0.6, \beta = 0$.

Branch and Bound Algorithm:

Step 0: initial solution. Generate x_i randomly by 0-1, then calculate its TLCC as an initial upper bound. For example, $TLCC\,(X^0) = TLCC\,(1,0,1,0,1,1) = -69.0$. Also we can calculate its relaxed solution is -88.6, as a lower bound. The result is shown in the top of Figure 6.

Step 1 (end condition): if there is no any sub-problem then end the calculation. The Current upper bound is the optimal solution. Else go to step 2.

Step 2 (select variable in x_i for bound operation): the last generated sub-problems will be selected.

Step 3 (bound operation):

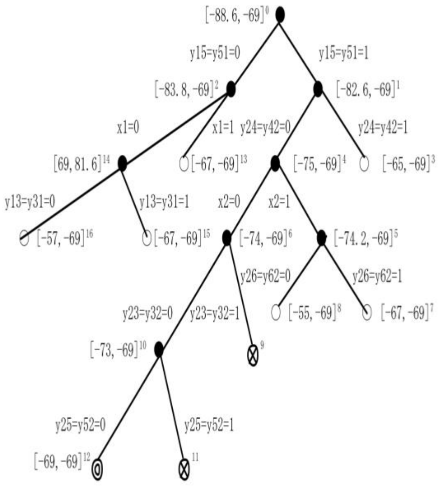
3-1: if the selected sub-problem is not feasible then end the sub-problem go to step1. For example, because $x_2 = 0$ is determined proviously, then the sub-solution of No.9 ($y_{23} = y_{32} = 1$) is not feasible.

3-2: if the selected sub-problem is feasible and its solution is smaller then upper bound, then exchange the upper bound by the solution of the sub-problem. Go to step 1.

3-3: if the selected sub-problem has a relaxed solution and it is larger then lower bound then end the sub-problem, go to step 1. Else the relaxed solution is smaller than lower bound it is selected as next branch, then go to step 4.

Step 4 (branch operation): select a variable which is not an integer and set it to be 0 or 1, go to step 1.

Repeat the algorithm we can obtain the optimal solution $X^* = (1,0,1,0,1,1)$ and the *TLCC* is -69, with just searching 16 sub-solutions. Notice that the searching process is depended on the initial solution because different x_i may lead different y_{ij} so that the searching process may take a long calculating time. For example, if $X^0 = (0,0,0,0,0,0)$ where all of interfaces are not used, the searching process should search 64 sub-solutions. Following we execute several numerical examples to show the utility and efficiency of the algorithm. In fact it is not reasonable to use all of interfaces, so that make an initial solution effectively can increases the



effective of calculation.

Figure 6 The search process of the B&B algorithm

6 NUMERICAL EXPERIMENTS

Using above proposed algorithm, we can solve large design problems, given C_i and ΔC_{ij} . We provide several numerical experiments to improve the effectiveness and efficiency of the algorithm. The parameters of the experiments are set as following: C_i is generated randomly by a normal distribution N(0.0, 1.0), ΔC_{ij} is generated randomly by a normal distribution N(0.0, 1.0/*N*). Set parameters $\alpha = \alpha' = 0.5, \beta = -0.6, \beta' = 0$. Calculations are executed by using a Window 7 notebook computer with a CPU (Intel Core™2@2.93GHz). The relaxed linear programming problem is solved with the interior point method packaged in Lingo 11.

6.1 The effeciency of the algorithm

Figure 7 shows the efficiency of the algorithm compared with enumerative method, where horizontal axis shows the scale of the functions (interfaces), and vertical axis shows the calculation times (seconds). The percentage of nonzero elements of the coefficients is set by 20%.

From figure 7, it can be observed that even both enumerative method and proposed B&B algorithm are exponential increasing types. Comparing with enumerative method (in a sharp curve), the proposed algorithm takes a slow curve in the range of the figure. For example, by using enumerative method only small design problem (with 6 or 8 devices) can be solved in a reasonable computational time, when the devices are over 10 it needs about over a day time to calculate the optimal solution, so in practice enumerative method is not useful to solve the design problem. However, by using our propose B&B algorithm, larger design problem (for example 16 devises) can be calculated in several minutes. That means the B&B algorithm is effective for solving the design problem and practical in real world because almost products are with smaller twenty module devices.

6.2 The effect of non zero elements of ΔC_{ij}

It can be found in the experiments that the calculation time is influenced by ΔC_{ij}. Figure 8 shows the experiments of different ΔC_{ij} in where the horizontal axis shows the percentage of non zero elements in ΔC_{ij}, vertical axis shows the calculation time. Two curves show different products with different devices (10 and 16 devices). It can be observed that the parameter ΔC_{ij} has a significant influence on calculation time, the more the percentage of non zero elements in ΔC_{ij}, the longer the calculation time.

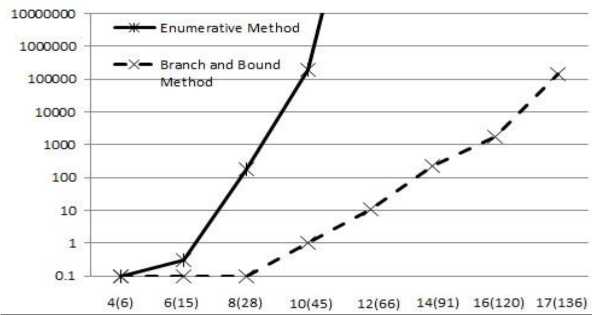


Figure 7 the efficiency of the B&B algorithm

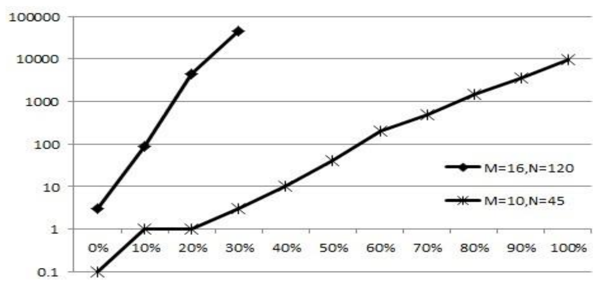


Figure 8 Calculation time of different ΔC_{ij}

7 CONCLUSIONS

We have studied product design combining integrity and modularity, where life cycle costing method is used as an evaluating function. And we also gave a clear explanation on the relationship between product architecture and life cycle cost. In this paper, our contributions are after illustrating the calculation complexity of the model, we transfered the model to a simple linear programming form without changing its identical feature, and proposed a branch and bound algorithm to solve the linear programming transformation model. We also provided numerical experiments to show the effect and utility of the solution method.

As a result, the calculation complex of the model needs us to develop effective solving algorithms. The detail analysis on life cycle cost functions of integrity also should be performed preferentially. We also should compare the calculated results to existent studies, to confirm the utility and performance of the model. Furthermore, heuristics or Meta algorithms are taken into account to up the calculation effective. These are our future works.

8 ACKNOWLEDGMENTS

This work is supported by the Japan Society for the Promotion of Science (JSPS) under the Grant No. 24510192.

9 REFERENCES

[1] Kaku, I., Masui, T., Otani, N. and Yin, Y.. 2012. Definition, model and algorithm of new product design considering life cycle and architectures, 10th Global Conference on Sustainable Manufacturing, Istanbul.

[2] Clark, K. B., Fujimoto, T. 1990. The Power of Product Integrity, Harvard Business Review, November-December, 107-118.

[3] Jiang, D., Shinzato, T., Kaku, I., Yin, Y. 2011. A mathematical model of product through integral architecture, Proceedings of the 21th International Conference on Production Research (ICPR-21), Stuttgart.

[4] Yin, Y., Kaku, I., Liu Ch. G. 2012. Product architecture, product development process, system integrator and product global performance, Production Planning & Control, iFirst, 1-17.

[5] Fabrycky, J.W., Blanchard, B.S. 1991. Life cycle cost and economic analysis. Englewood Cliffs, NJ.

[6] Ellram, L.M., Siferd, S.P. 1998. Total cost of ownership: A key concept in strategic cost management decisions, Journal of Business Logistics, 19(1), 55-84.

[7] http://www.toyota.co.jp/jpn/sustainability/environment/recycle/scrap/tech/bumper.html, sited at 28 June, 2012.

[8] Ulrich, K., Eppinger, S. D. 1994. Product Design and Development, McGraw-Hill, New York.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

13.4 Energy saving innovative design of green machine tools by case-based reasoning

J. L. Chen[1], I.-T. Shen[1], H.-C. Huang[2]
[1] Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan
[2] ITRI, Taichung, Tauwan

Abstract
This paper presents a methodology for eco-innovation that integrates examples of effective energy-efficient practices in the machine tool industry, case-based reasoning (CBR) and TRIZ in energy saving design of green machine tools. An index system that combines the eco-design and function performances of green machine tool and energy saving technology is proposed. Designers can easily utilize prior cases to redesign a new product and satisfy the both performances. the knowledge for solving energy-saving problem can be supported by examples of effective energy-efficient practices in the industry. Then, TRIZ tools are introduced to modify the knowledge to obtain new designs. A case study is used to explain the capabilities of the proposed methodology.
Keywords:
Green machine tools, Energy saving, Case-based reasoning, TRIZ, Eco-innovation

1 INTRODUCTION

Global warming has become a topical issue in recent years. Main source of carbon dioxide emissions that affects global warming is from electricity generation, transportation, and industry demand. In order to solve global warming problem and reducing CO2 emissions, the international society begin a joint effort to seek for the low carbon and energy saving products. As for machine tools, the ErP regulation of EU and ISO 14955 all deal with the energy saving issue in machine tools. Therefore, it has growing needs for product energy saving innovation tool for machine tools.

The use of TRIZ method in eco-innovative design tasks is one of the interests, which have been proposed since 2000 [1-2]. They identified ways in which tools and methodologies from TRIZ might be used in eco-innovation. Chen and Chang [3] present eco-innovative design methods to help designers developing energy saving products. However, although TRIZ method can facilitate the production of innovative ideas, forming such ideas still heavily relies on user experiences. Although humans can recall many experiences, memories are still limited and may be forgotten when needed.

Generally, it is convenient to utilize designers' prior experience to make a new product, and to this end a method known as case-based reasoning (CBR) [4] was developed to make more efficient use of this. CBR has been extensively adopted in fixture design [5] and eco-design 6-8]. Zeid *et al*. [7] developed a system that utilizes CBR to solve the planning of disassembly problems. Veerakamolmal and Gupta [6] presented a procedure to initialize a case memory for different platforms and used a system of CBR to determine disassembly processes. Shih and Chang [8] used a CBR procedure to find the best strategy for End-of-Life (EOL) electronic products. Yang and Chen [9-11] developed an innovative design model that integrates examples of effective energy-efficient practices in industry, CBR method, and TRIZ tools to achieve the eco-innovation objective.

This paper presents an eco-innovation method to support designers to develop energy saving machine tools by using case-based reasoning (CBR) and TRIZ 40 inventive principles. Design procedures for eco-innovation of energy saving machine tools are proposed. A machine tool case is presented to demonstrate the capability of the proposed method.,

2 CASE-BASED REASONING (CBR) METHOD

As a problem solving method, CBR imitates human thinking during problem solving based on previously successful experiences. Such experiences are described as case patterns to store in a database. Preliminary case information describes the problem and offers a relevant solution. CBR comprises the following stages: identifying the current problem, locating similar previous cases in the database, proposing a satisfactory solution based on those cases, evaluating the feasibility of the solution and storing it into a database to enhance its problem solving capability. The CBR framework can be illustrated a cycle that consists of retrieval, reuse, revision and retention [15].

1. Retrieval: This stage identifies cases from the database to resolve the current problem. A problem is defined by a list of the parameters with values, while the index system instructs them to identify the most similar cases. The retrieved cases are evaluated by calculating the similarity function. Consequently, the most similar problem and its solution are identified.
2. Reuse: A situation in which the most similar solution is a perfect match implies that the cycle has achieved its goal. Unfortunately, the retrieved case can likely only match the problem to a certain extent, implying that the related solution is a sub-optimal one and requires a revision process.
3. Revision: Revision involves adjusting the parameters of the retrieved solution to conform to those of the current

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

problem. The revision often requires additional knowledge that can be represented by certain rules, heuristics or domain knowledge.

4. Retention: The verified solution is stored into the database. Only solutions that contribute to the future development of solutions should be stored.

3 TRIZ METHODS

3.1 Contradiction matrix and 40 inventive principles

When a design engineer tries to solve an innovative design problem, it is usually a system incompatibility or conflict design problem. As the designer changes certain parameters of the system in his design problem, it might make other compromise with this kind of contradiction situations and restricts himself on performing innovative design tasks. The TRIZ method was developed in the former Soviet Union by Altshuller, who had analysis over 400,000 patents to build the contradiction matrix and 40 inventive principles. For using TRIZ method in innovative design problem solving, the designer needs to first find corresponding contradictions for his problem at hand. Next, the designer matches the meaning of each contradiction with two appropriate parameters from 39 engineering parameters that defined in the TRIZ contradiction table [12]. The designer can find 3-4 most frequency used principles for solving innovative design problem from contradiction matrix when he confirms the parameters of contradiction for an engineering system.

4 METHOD FOR ENERGY SAVING INNOVATION OF MACHINE TOOLS

The flowchart in Figure 1 describes a model for preliminary eco-innovation energy saving design in machine tools that integrate the CBR and TRIZ method. The retrieval, reuse and revision processes in the CBR framework allow a novel design to satisfy functional performances. Next, TRIZ tools are introduced to devise innovative solutions for the redesign functional performance in order to achieve eco-innovation is new energy saving machine tool design. Each step is described in detail as follows.

4.1 New machine tool design information

Product design information is comprised of its functional performances. In this approach, 29 green machine tools and 113 examples of energy-efficient practices that have proven effective in various fields are collected and indexed in a database.

Three types of index system are developed in this study for machine tool, component and energy saving, respectively. The definition of each index for different index system is illustrated, as follow.

For machine tool index system, index 1 refers to the function of machine tool. Index 2 is the output of the machine tool. Index 3 is the input of machine tool. Index 4 refers to the force field of machine tool, while index 5 is the energy saving design concept of machine tool. Table 1 gives the details of these indices.

As for component index system, The eight functional performances are type of component, function of component, output, input, force field, sub-system, super-system and energy saving design concept. Table 2 lists the details of these indices in the index system.

Five functional performances with various situations refer to energy saving case in an index system. The five functional performances are function, output, input, force field and energy saving design concept. Table 3 lists each functional performance in the index system.

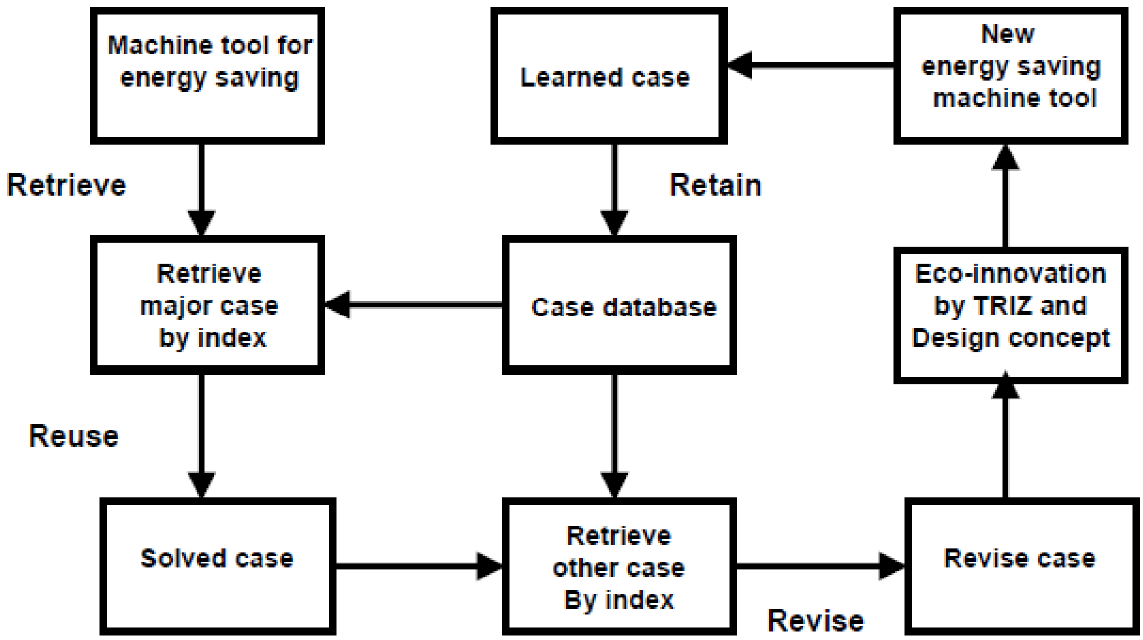


Figure 1: The model for energy saving eco-innovation of green machine tools by CBR and TRIZ.

Table 1: Partial index description of machine tools

Weight	Index	Index Name	Partial Index Value
0.3	1	Function	Milling, 5-axis NC, None
0.2	2	Output	Machined Part
0.2	3	Input	Material
0.2	4	Force Field	Mechatronics
0.1	5	Design Concept	Direct Drive, Geometry, Optimum, Modular

Table 2: Partial index description of components

Weight	Index	Index Name	Partial Index Value
0.1875	1	Type	Tool, Spindle, Control Unit, Motor, Computer
0.1875	2	Function	Power Balance, Cutting Force, Energy Data
0.125	3	Output	Energy, Information
0.125	4	Input	Energy, Information
0.125	5	Force Field	Mechatronics, Electricity,
0.126	6	sub-system	Control, Motor, Structure
0.0625	7	super-system	Milling, Turnning, NC tool
0.0625	8	Design Concept	Modular, Geometry, Direct Drive, Dry Cutting,

Table 3: Partial index description of energy saving cases.

Weight	Index	Index Name	Partial Index Value
0.3	1	Function	Improving Efficiency, Provide Electricity, Produce Fuel/Energy
0.2	2	Output	Electricity. Energy, Fuel, Information
0.2	3	Input	Solar power, Human power, Energy, Information, Material
0.2	4	Force Field	Chemistry, Mechatronics, Electricity, Mechanical power, Fluid Power
0.1	5	Design Concept	Modular, Geometry, Optimum, Human power, Bionics, Reuse Energy

4.2 Retrieval, reuse and revision processes in the CBR framework

For retrieving cases, similarity calculation helps designers to obtain the most closely matching case in a database. The total similarity value is the summation of each similarity value multiply to its weighting value, as shown in Equation (1).

$$\text{Total similarity} = \frac{\sum_{i=1}^{n} w_i \times sim_i(f_i^l, f_i^R)}{\sum_{i=1}^{n} w_i} \quad (1)$$

where w_i is the weight of the ith index; i is the subscript for ith index; n is the number of indices; sim_i is the similarity of the i index between new and previous cases; f_i^l is the value of index i of the new case; and f_i^R is the value of index I of the retrieved case. The value of $sim_i(f_i^l, f_i^R)$ is that if $f_i^l = f_i^R$ then sim_i =1, else sim_i =0. The weight w_i varies among (0,1) and summation of all w_i is equal to 1. Designers set the importance of each weight. In this approach, the importance level of each weigh is set by three levels, most importance, medium, and less importance, by assigning value of 3, 2, and 1, respectively.

For the index system of machine tool, function (w1) is the most importance with assigning value of 3. As for design concept (w5) is less importance with assigning value of 1. Therefore, the weighting value of w1 is 0.3 (3/(3+2+2+2+1);) w2, w3, and w4 are 0.2 (2/(3+2+2+2+1)); and w5 is 0.1 (3/(3+2+2+2+1)).

A situation in which the retrieved case matches all input indices implies that the case is directly reused as the conformed solution and the next step is taken; otherwise, the designers should revise it to new solution. In the case-modification step, the system searches the database again to retrieve another case containing suitable parts and, then, replaces the parts of the former case with suitable parts from the new case.

4.3 Enhancement of energy saving to achieve eco-innovation by TRIZ

Current 29 green machine tools and 113 innovative energy saving products or technologies are searched as design cases. Design cases are analyzed to identify which TRIZ inventive principles they might use. Therefore, each case in case base has some related TRIZ inventive principles. After the CBR system retrieve similar cases, the TRIZ inventive principles associated with those similar cases can be used for the designer as eco-innovation tool to generate new idea for problem at hand.

A table with design concepts and related TRIZ inventive principles is developed to match the design concept with TRIZ innovative principles, as shown in Table 4. Therefore, once the designer obtained the design concept of retrieved cases from the CBR system, he using TRIZ innovative principles for his energy saving innovative design task will have some specific ideas of what to do.

Those TRIZ inventive principles appearing most frequently will have a better chance of success in solving energy saving eco-innovation problems. Therefore, the designer can solve eco-innovative design problems by choosing those most commonly occurring TRIZ inventive principles based on information in each case and Table 4

4.4 New energy saving machine tool case store

The new energy saving green machine tool solution is stored in the case base when the modification come from the designer is finished and becomes the CBR system's new knowledge. Hence the CBR system can learn from itself by expanding the case base whenever it solves a new energy saving machine tool design problem.

Table 4: Design concepts and the related TRIZ principles

Design Concept	Related TRIZ Inventive Principles
Geometry	#1、#2、#3、#4、#5、#7、#13、#14、#26
Reuse	#23、#25、#27、#34
Weight Reduction	#2、#16、#35、#40
Polymer	#16、#35
Feedback	#10、#16、#23、#24、#25
Modular	#5、#10、#25、#26、#27、#34
Optimum	#16、#22、#23、#25
Change Material	#11、#27、#30、#31、#32、#34、#35、#40
Direct Drive	#2、#5、#10、#28
Dry Cutting	#2、#21、#22、#27、#29
Variable Speed Drive	#16、#20、#21、#23、#28

5 ENERGY SAVING INNOVATION SOFTWARE TOOL OF MACHINE TOOLS

In this study, a Chinese language based simple software – energy saving innovation software tool for machine tool is developed. The purpose is to assist automation in using the pro[posed CBR method in energy saving eco-innovation of machine tool for SMEs of machine tool in Taiwan. This energy saving innovation software tool of machine tool is developed by using Microsoft Excel 2007 software. The interface page of this tool are illustrated in Figure 2,. As shown in Figure 2, the upper three lines in the interface page is the weight of each index, the name of index, and the value of index of designing machine tool, respectively. The lower part of the interface page is the index value and associate TRIZ inventive principles for each case in the case base. The first left column in the interface page is the similarity value of each case .in case data base.

The designer is requested to input the index value of designing machine tool. This CBR software system will automate to change the matching index into brown color, as shown in Figure 2. The first left column also will change the color of each case from green to light green by the decreasing order of the similarity value. The designer can based on the color to find out the cases with the same similarity value.

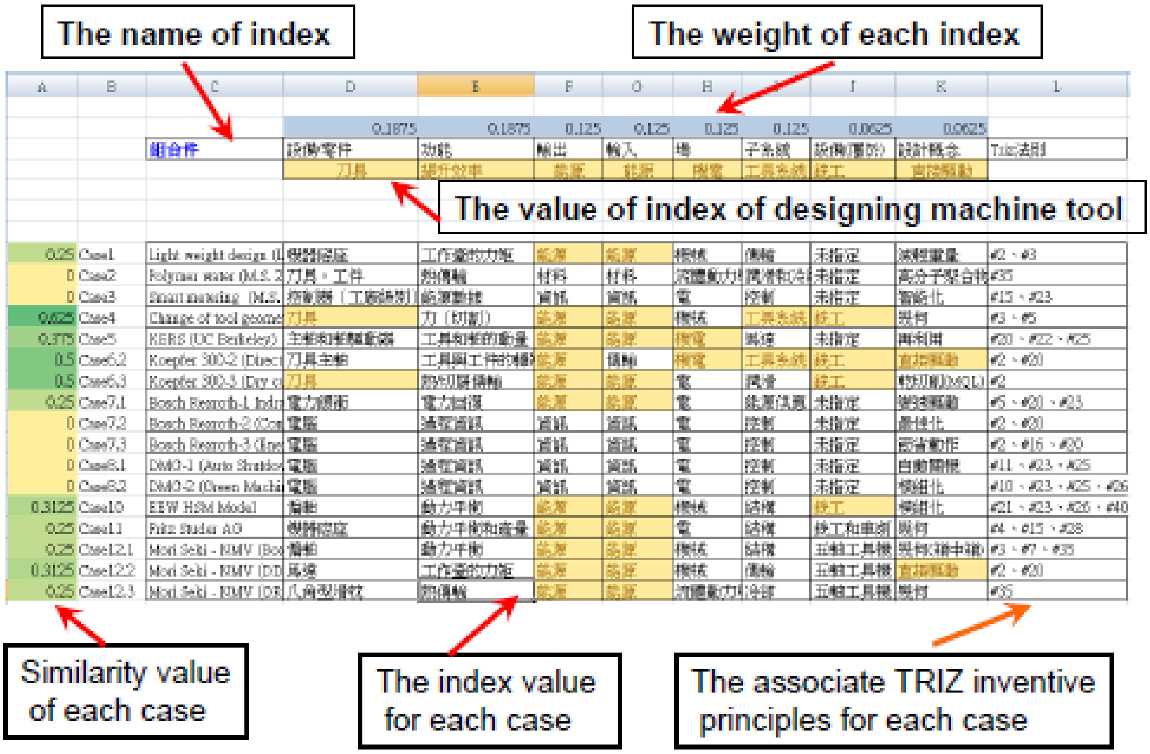


Figure 2: The interface page of energy saving innovation software tool of machine tool

At the bottom of the interface page, as shown in Figure 3, a menu with 3 types index and design concept can be chosen by the designer at performing the energy saving eco-innovation design task for machine tools.

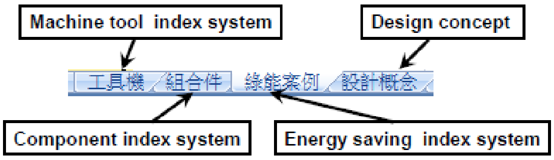


Figure 3: A menu in the interface page of CBR system

6 EXAMPLE

6.1 Problem description

The EMVC machine tool designed by ITRI is selected as design example to prove the capabilities of proposed method and developing software tool. This machine tool can be divided into six subsystems, such as tool magazine, working table, column, base, saddle, and headstock. The Index of EMVC machine tool is shown in Table 5. The index value of five functional performances are none, machined part, material, mechatronics, and none.

Table 5: Index selection of the EMVC machine tool

Weight	Index	Index Name	EMVC
0.3	1	Function	None
0.2	2	Output	Machined Part
0.2	3	Input	Material
0.2	4	Force Field	Mechatronics
0.1	5	Design Concept	None

6.2 Retrieval, reuse and revision processes in the CBR framework

Input the index value (Table 5) of the EMVC machine tool into the energy saving innovation software tool for similarity calculation, as shown in Figure 4. According to the similarity calculation results in Figure 4, the software tool display the highest similarity cases with similarity value of 0.9 are both “Bosch Rexroth” and “DMG” cases. The information of index system for “Bosch Rexroth” and “DMG” cases are shown in Table 6 and Table 7, respectively.

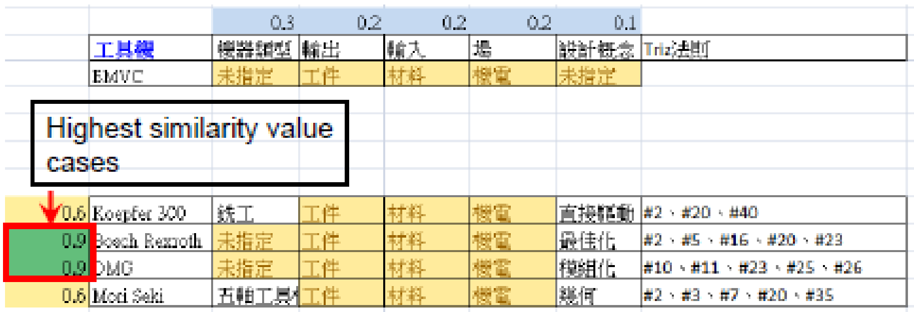


Figure 4: Retrieval case of energy saving innovation software tool of the EMVC machine tool.

.Table 6: Information of the Bosch Rexroth Case

Weight	Index	Index Name	Bosch Rexroth
0.3	1	Function	None
0.2	2	Output	Machined Part
0.2	3	Input	Material
0.2	4	Force Field	Mechatronics
0.1	5	Design Concept	Optimum
		TRIZ principles	#2、#5、#16、#20、#23

Table 7: Information of the DMG case

Weight	Index	Index Name	DMG
0.3	1	Function	None
0.2	2	Output	Machined Part
0.2	3	Input	Material
0.2	4	Force Field	Mechatronics
0.1	5	Design Concept	Modular
		TRIZ Principles	#10、#11、#23、#25、#26

Both cases have same index value with the EMVC machine tool on index 1 , index 2, index 3 and index 4. Only index 5 (design concept) is in different value. Therefore, one can do second search for the other cases by using this index 5. However, the index 5 of the EMVC machine tool does not have any meaningful index value (the design concept for the EMVC machine tool is “none”, as shown in Table 5). The retrieval action for search other matched cases is stopped. The innovation process turns to next step by using associated TRIZ inventive principles in the major “Bosch Rexroth” and “DMG” cases.

6.3 Enhancement of energy saving to achieve eco-innovation by TRIZ

Based on Table 4, Table 6, and Table 7, one can collected all associated or related TRIZ inventive principles together and count the appearance time of each TRIZ principle as shown in Table 8.

Table 8: The number of appearance of TRIZ principles

Number	TRIZ Inventive Principle
3	#23、#25
2	#5、#10、#16、#26
1	#2、#11、#20、#22、#27、#34

As shown in Table 8, the most frequency appearance TRIZ inventive principles are #23 (Feedback) and #25 (Self-service). Both TRIZ inventive principles suggest an idea to take advantage of a feedback system that allows the machine tool to be able to monitor the whole situation,. Therefore, the unnecessary use of energy in machine tool can be reduced or closed.

6.4 New energy saving machine tool case store

The new energy saving green machine tool solution is obtained. Therefore, one can store the EMVC machine tool case into the case base. Since the new innovative idea comes from the design concept of "feedback", The index 5 (design concept) of the EMVC machine tool case can change from "none" to "feedback". Furthermore, the associated TRIZ inventive principles #23 and #25 can be recorded into the EMVC machine tool case. The EMVC machine tool case becomes the new learned knowledge of the energy saving innovation software tool.

7 SUMMARY

This paper proposed a methodology for eco-innovation that integrates examples of effective energy-efficient practices in the machine tool industry, case-based reasoning (CBR) and TRIZ in energy saving design of green machine tools. An index system that combines the eco-design and function performances of green machine tool and energy saving technology is proposed. A Chinese language based simple software – energy saving innovation software tool for machine tool is developed. The innovative result of case study, a feedback system that allows the machine tool to be able to monitor the whole situation, for reducing energy consumption is currently used in some new developing green machine tool. The capabilities of the proposed methodology are verified..

8 ACKNOWLEDGMENTS

This Study is supported by The Intelligent Machinery Technology Division, Mechanical and Systems Research Laboratories, ITRI (Industrial Technology Research Institute) of Taiwan.

9 REFERENCES

[1] Jones, E., D. Harrison, Investigating the Use of TRIZ in Eco-Innovation, The TRIZ Journal, September, 2000..

[2] Low, M.K., Lamvik, T., Walsh, K., O. Myklebust, Product to Service Eco-Innovation: The TRIZ Model of Creativity Explored, Proceedings of 2000 International Symposium on Electronics and the Environment, San Francisco, California, May 8-10, 209-214

[3] Chen, J.L, Chang, J.H., 2010, A TRIZ Based Eco-innovative Design Method for Energy Saving Products, 17th CIRP International Conference on Life Cycle Engineering, *LCE2010*, Hefei, China, May 19-21.

[4] Kolodner, J., 1993, Case-based reasoning. Morgan Kaufmann Publishers, SanMateo, CA.

[5] Sun, S.H., Chen, J.L., 1996. A Fixture Design System Using Case Based Reasoning, Engineering Application of Artificial Intelligence, 9/5, 533-540.

[6] Veerakamolmal, P., Gupta, S. M., 2002, "A Case-Based Reasoning approach for automating disassembly process planning", Journal of Intelligent Manufacturing, 13/1,.47-60.

[7] Zeid, I., Gupta, S.M., Bardasz. T., 1997, A Case-Based Reasoning Approach to Planning for Disassembly, Journal of Intelligent Manufacturing, .8/2,. 97-106..

[8] Shih, L.H., Chang, Y.S., Lin, Y.T., 2006, Intelligent Evaluation Approach for Electronic Product Recycling via Case-Based Reasoning, Advanced Engineering Informatics, 20 /2, 137-145.

[9] Yang, C.J. Chen, J. L., 2012, "Energy-saving eco-innovation using eco-product cases with CBR and TRIZ tools", Journal of the Chinese Society of Mechanical Engineers., 33/.4, 507-515.

[10] Yang, C.J. Chen, J. L., 2011, "Accelerating preliminary eco-innovation design for products that integrates Case-Based Reasoning and TRIZ method", Journal of Cleaner Production, 19, 998-1006,

[11] Yang, C.J. Chen, J. L., 2012, "Forecasting the design of eco-products by Integrating TRIZ evolution patterns with CBR and simple LCA methods", Expert Systems With Applications. 39, 2884-2892.

[12] Terninko, J., Zusman, A., Zlotin, B., 1998, Systematic Innovation: An Introduction to TRIZ, St. Lucie Press, Boca Raton, FL

GCSM 11th Global Conference on Sustainable Manufacturing
2013 23rd - 25th September Berlin - Germany

13.5 The innovative waste container for sustainable cities

B. Yilmaz[1], Z. Yilmaz[1], M.R. Yesil[1], H. Karabudak[1] and O Gezgin[2]
[1] Department of Chemical and Process Engineering, Bilecik Seyh Edebali University, Turkey
[2] Deputy Mayor of Bilecik Municipality, Bilecik, Turkey

Abstract

Nowadays, the municipalities needed to solve problems about waste collecting and transporting process for a sustainable urban development; humidity, foul odor, load factor of vehicle increases, collecting period and fluid leakage. For a sustainable waste management these problems can be eliminated. The innovative waste container decreased waste's amount, collecting and transporting costs, exhaust emissions and stench. The traffic problems, exhaust emissions, fuel and labor costs decreased with low waste collecting process. Additionally, waste monitoring system supported waste management collaterally waste's storage, collecting and transporting route optimization. Solid waste storage area capacity increased due to wastes transported to waste storage area decreased. This system will contribute the successful examples of climate-friendly cities all over the World.

Keywords: municipal wastes, waste collecting and transporting, innovative waste container

1. INTRODUCTION

Sustainable urban development is a consolidation of natural resource and socio-economical development. For a sustainable urban development key concepts are energy, transportation, health and design according to the sun.

According to UN population fund for the year 2011, the World's population is about 7 billion that a half of people live in cities and as an estimate the World's population's 70% will live in cities in 2025. Also, according to UN Habitat data, the cities are responsible for 75% percentage of World's energy consumption and 80% percentage of global greenhouse gas emissions. As a result of global climate change; climatic extremes, drought, floods, food insecurity, loss of biodiversity, extinction of species, mass migration and the emergence of social explosions which cause to transform cities more brittle structure.

In a reaction to daily life's show up wastes in associated with urbanization, is an important research area within partaking versatile relations between executive, technical, economical and social disciplines. Today, the amount of wastes and recover, eliminate and appraisal cost of them is scaled with nation's income (Table 1) and these costs expect to increase more in the future (Table 2). Also, the composition of waste is associated with level of income (Table 3).

Wastes have two important effects as a terms of sustainability. The first one, waste generation are indicating to how effective or efficient usage of resource. The second one, how the wastes removed with economically and environment-friendly [2]. Also environment impacts of wastes are such as to biological, chemical and physical. Hansen disease, plague, cholera, dysentery, tuberculosis, hydrophobia and malaria are the examples of biological negation, which infect directly or via insects; composed to percolating water and gases induce chemical and biological negations in waste deposit area. Additionally wastes released to the environment randomly, physically able to harm humans also.

In 2011, Turkey have $10444 GDP per capita with 74,7 million people that 76,8% live in cities and totally 2949 municipality, 16 of them are metropolitan municipality provide service to these people. Turkish municipalities have set priorities for generalize sustainable applications with "Declaration of Climate Friendly Cities" in the Conference of Sustainable Cities in Turkey at 15 November 2011.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

Table 1. Estimated Solid Waste Management Costs by Disposal Method*[*][1].

	Low income countries	Lower mid inc countries	Upper mid inc countries	High income countries
Income (GNI/capita)	<$876	$876-3,465	$3,466-10,725	>$10,725
Waste generation (ton/capita/yr)	0.22	0.29	0.42	0.78
Collection efficiency (percent collected)	43%	68%	85%	98%
Cost of collection and disposal (US$/ton)				
Collection**	20-50	30-75	40-90	85-250
Sanitary landfill	10-30	15-40	25-65	40-100
Open dumping	2-8	3-10	NA	NA
Composting	5-30	10-40	20-75	35-90
Waste-to-energy incineration	NA	40-100	60-150	70-200
Anaerobic digestion	NA	20-80	50-100	65-150

* *All values provided in the table are exclusive of any potential carbon finance, subsidies, or external incentives. Costs included are for purchase (including land), operation, maintenance, and debt service.*

** *Collection includes pick up, transfer, and transport to final disposal site for residential and non-residential waste.*

Table 2. Estimated Solid Waste Management Costs 2010 and 2025 [1].

Country Income Group	2010 Cost	2025 Cost
Low income countries	$1.5 billion	$7.7 billion
Lower mid inc countries	$20.1 billion	$84.1 billion
Upper mid inc countries	$24.5 billion	$63.5 billion
High income countries	$159.3 billion	$220.2 billion
Total Global Cost (US$)	$205.4 billion	$375 billion

Table 3. Types of Waste Composition by Income Level (current and (2025) estimates) [1].

Income Level	Organic (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Other (%)
Low income	64(62)	5(6)	8(9)	3(3)	3(3)	17(17)
Lower middle income	59(55)	9(10)	12(13)	3(4)	2(3)	15(15)
Upper middle income	54(50)	14(15)	11(12)	5(4)	3(4)	13(15)
High income	28(28)	31(30)	11(11)	7(7)	6(6)	17(18)

Waste management in Turkey as well as all around the world is important for both people and environmental health, and economic aspects. For this reason wastes are collecting, transporting, deposition and eliminating properly in urban area. Also in the whole process of eliminating wastes, waste collecting is the main cost of this sections and 65-95% in total cost [3]. According to statistics from Turkey Statistical Institute (TUIK), out of waste collecting and transporting operations expenses in Turkey are in between 23-74 €/tone (30-95 $/ton). These costs are depended on topographical features of zone, fuel and labor cost and collection period, cover a distance and load factor of vehicles. Additionally, about 50% average load factor of vehicle increases collecting and transportation costs.

According to results of the survey of municipal waste statistics (Turkish Statistical Institute) [4], in 2010 collected 25,28 million ton wastes (14,43 million tone in summer, 10,85 million tone in winter) and 54,4% of these wastes are going through the waste deposit areas, %43,5 of them are going to municipal's dump, 0,8% of them are going to composting plants 1.3% of them eliminating with other methods.

The average daily amount of waste generation in Turkey is 1.0 kg/person-day and according to 2011 census data, 74,700 ton/day. If the average cost of collection of 50 €/ton according to Table 1, the daily cost will be € 3,735,000. In 2011, gross domestic product (GPD) of Turkey's was $ 772,3 billion and the waste collecting and transportation cost was $ 987,2 million which is 0,13% for Turkey GPD's.

1.1. Characteristics of Municipal Wastes

The municipal wastes; household, industrial, commercial, institutional and municipal wastes [5]. Especially, this concept doesn't cover by the harmful and hazardous solid wastes.

The amount and characteristics of municipal waste are depends on many factors. These factors are social, cultural, economic status and eating habits of the residents, The municipal wastes contains food wastes as organic structures are easily separated and its moisture content is very high (Table 4).

Table 4 Proximate analysis of municipal waste [6]

Waste type	Moisture content	The amount of liquid	Carbon	Ash
Food	70,0	21,4	3,6	5,0
Wood	19,2	65,0	15,0	0,8
Paper/cardboard	10,2	75,9	8,4	5,4
Plastic	0,2	95,8	2,0	2,0
Textile/Rubber/Leather	7,8	69,0	16,2	7,0
Glass	2,0	-	-	96-98

1.2. Organization of Municipal Wastes

The main concepts for organization of municipal wastes; generation and accumulation of waste, collecting, transporting and recycling. These are;

a) Generation of waste: The wastes are constituted by various resources.

b) Accumulating of waste: The wastes are accumulated without harming community health care and for that purpose waste bin and containers are using to accumulation process of wastes.

c) Collecting and transporting: The process makes by vehicles which are open or close top, and compression systems or not.

d) Recycling: Not recycled wastes are eliminating includes recycled wastes transformed with various physical/chemical process.

Thereby wastes accumulating in large containers, and collecting all the way extended period of time is preferred economically. But, this situation especially makes fluid leakage, insects and the stench with temperature increase in hot weather. This problem can be solved with collecting in short period of time, but this is decreases the rate of occupancy in garbage trucks and increases costs of collecting. Consequently; sustainable waste collecting and transporting processes main problems need to be resolved for today are;

- **Humidity:** The cost of waste transporting increased with wastes 15-20% average moisture,
- **Foul odor:** This results from bacteria increases in humid environment, also cause to gather flies and other insects,
- **Occupancy:** High moisture and low density reduces the rate of occupancy of wastes,
- **Collecting period:** As the period decreases, container and occupancy and efficiency of vehicles decrease.
- **Fluid Leakage:** Pollute the environment; create stink and damaging mechanical systems.

The main aim of this study is to design and prototyping with waste container to contribute the solution of municipal waste collecting and transporting also emissions of greenhouse gases problems in Bilecik province.

2. MATERIALS AND METHODS

2.1. Materials

The materials to be used in this study are a waste container, solar panel and battery, sunlight focusing system (Fresnel lens, main board cooler for computer and air fan) UV-C reactor (UV-C lamp and metal tube), remote area monitoring system, temperature-humidity meter device, and metal tubes with a PC air fan. These are;

a) **Waste container:** A container which is 1 m^3 voluminous waste storing case, domestic solid wastes temporarily store before collecting wastes.

b) **Solar panel:** A system directly converts sunlight to electric current and stored in a battery.

c) **Sunlight focusing system:** This system is produced a Fresnel lens, PC's main board cooler and air fan.

d) **Fresnel lens:** A lens which can control the light direction coming from the different directions.

e) **Main board cooler:** The device absorbs and removes heat from the heat converting area with the aid of a air fan contact thereby the metal surface above main board.

f) **UV reactor:** This system was produced using a UV-C lamp and cylindrical metal tube body.

g) **UV-C lamp (254,3 nm):** Ultraviolet light fall into the range between 100-400 nm in electromagnetic spectrum and It has lethal effect on microorganisms like bacteria, virus, protozoa, mould, yeast and algae [7-9]. The reason is that, prevents repair and reproduction on cells thereby cell DNA's thymine dimmers cross linking [10]. The maximum lethal effect is observed between 250-270 nm [11].
h) **Remote monitoring system:** Collects and saves data from connected sensor. The device sends an e-mail or SMS when digress from determinate threshold value.
i) **Temperature and humidity meter:** The device measures temperature and humidity.
j) **Metal tubes:** To use for material transport.
k) **Air Fan:** The electrical device that provides air movement.

2.2. Method

The system, which decreases humid level, prevents stink and fluid leakage, increases occupancy and collecting period, according to the design problem to be solved in order to sustainable waste collecting and transporting. For this purpose, the design is formed UV-C for stink and disinfection, solar dryer for humidity, remote monitoring system set down for occupancy and collecting period.

a) **Foul odor and disinfection:** UV reactor, which has 10 cm of diameter and 35 cm length, designed and manufactured from stainless steel body, includes supply voltage 12 V and power 8W and wavelength 254,3 nm of UV-C lamp. In addition to the device includes a air fan and channels to set out the air flow.
b) **Drying of the humidity:** Generally, drying removes the volatile matters to obtain solid product [12]. The water molecules are bonded with a weak chemical bond and generate vapor pressure lower than pure liquid. Drying process occurs with hot temperature. Hot temperature is obtained with the aid of a sunlight focusing system. Turkey's average sunshine duration apprised 2640 hours per year (7,2 hours per day), average radiance intension apprised 1311 kWh/m^2-year (3,6 kWh/m^2 per day) (Table 5). According to these data, sunlight focusing system was designed and manufactured
c) **Remote monitoring system:** Temperature, humidity and level measurement values of waste bin, It send to the receiver as a SMS/e-mail

Table 5. Solar Energy potential of Turkey [13]

Months	Solar energy		Sunshine (hours/ mount)
	kcal/cm^2-month	kWh/m^2-month	
January	4,5	51,8	103,0
February	5,4	63,3	115,0
March	8,3	96,7	165,0
April	10,5	122,2	197,0
May	13,2	153,9	273,0
June	14,5	168,8	325,0
July	15,1	175,4	365,0
August	13,6	158,4	343,0
September	10,6	123,3	280,0
October	7,7	89,9	214,0
November	5,2	60,8	157,0
December	4,0	46,9	103,0
Total	112,7	1311,0	2640,0
Average	308,0 cal/cm^2-day	3,6 kWh/m^2-day	7,2 hour/day

3. DESIGN AND PROTOTYPING

3.1. Design

The designed process is a container which use solar energy for decreasing greenhouse gases, waste collecting, transferring and transport costs. The containers itself specified as the system. The systems inputs are wet waste, hot air and electrical energy. The system produces stink, fungus and bacteria. The system's expenses are using electrical energy in fan and control system with heat energy for drying and dehumidification. The system's outputs are dried solid waste with odorless humid air with no bacteria or fungus. The temperature and humidity values of the process controlled via remote monitoring system.

The process and equipments realized with flow chart and algorithms to make mass, energy and momentum equivalent (Figure 1).

3.2. Prototyping

The process and equipment designed system's equipments are used to manufacture a prototype for a model which includes whole specialties of design, and achieved the best performance of ergonomic, quality, economic and solidity.

The prototype has solar panel and battery, focusing system (Fresnel lens, main board cooler and fan), UV-C reactor (UV-C lamp and reactor wall), remote monitoring system, fans and tubes over a waste container, assembled or manufactured to be constituted in accordance with design data (Figure 2).

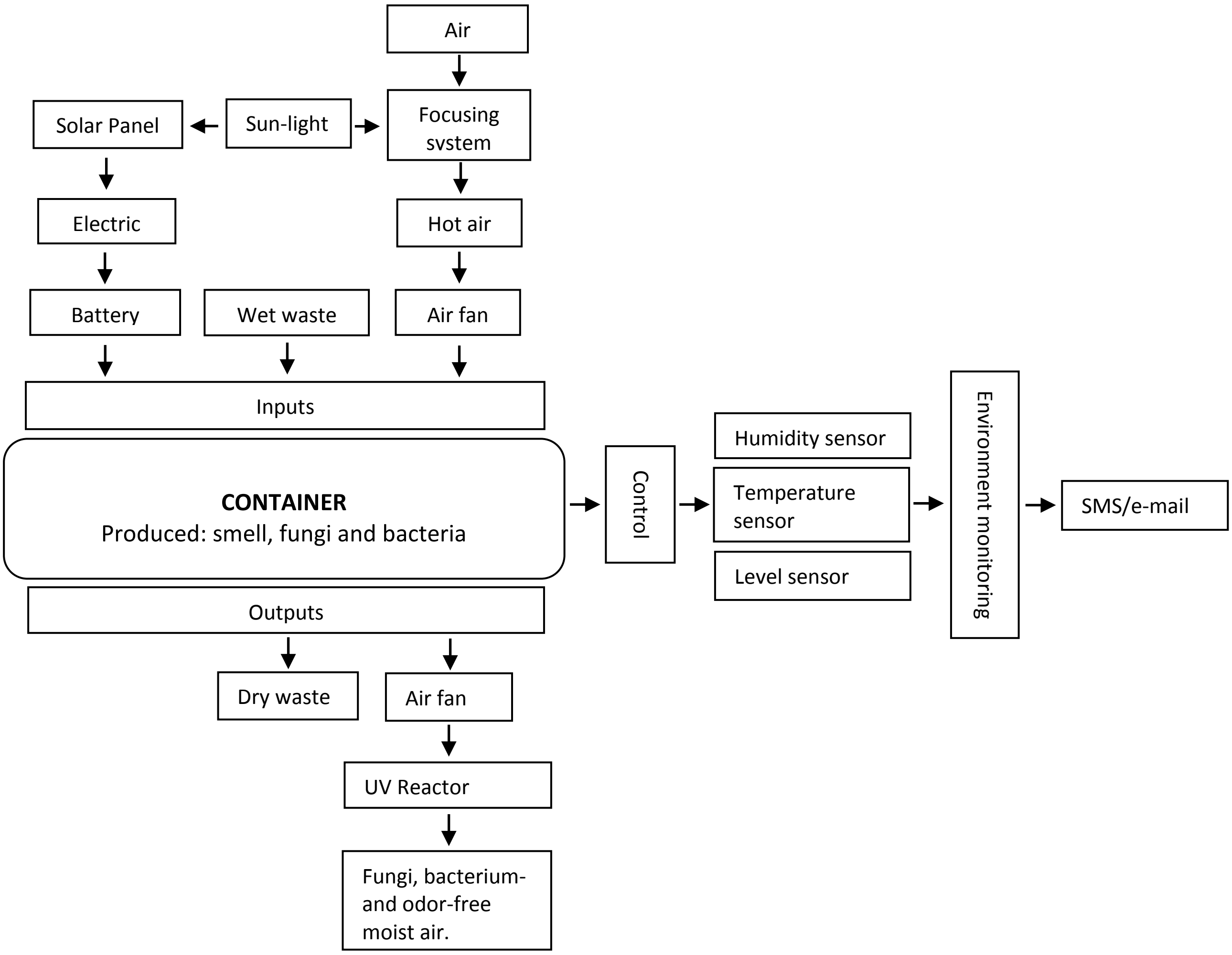


Figure 1. Process flow chart

Figure 2. Prototype

4. CONCLUSIONS

Nowadays, while population increases, municipal wastes amount and components, environmental issues and costs increase in parallel with technological evolutions, industrialization and urbanization. This study was performed in order to contribute to the solution of these problems. According to the results of this study;

- Solar drying of waste, increases the rate of occupancy of containers,
- Dried waste, reduces the costs of collection and transportation,
- Reducing the moisture content, also reduces the formation of methane gas,
- Application to container air of UV-C irradiation, reduces the occurrence of foul odor,
- Reduction of foul odor decreases the pest population. After all, pest control time and costs are reduced,
- Disinfected waste contributes to the protection of public health,
- Reduction of waste collection and transport operations, decreases; traffic problems, exhaust gas emissions, reduce fuel and labor costs,
- The remote monitoring system, the level of waste and the dryness tells you by SMS or e-mail. This system support optimization of the route, depositing, collecting and transporting by waste management system
- The waste minimization in disposal area increases the capacity of the solid waste storage areas,
- This innovative product; contribute to a cleaner environment and high level of hygiene in cities and pay for itself in a very short period of time.

In the world; the developed sustainable applications have wide effect on waste formation, collection and transportation. Available waste container's designs have no sustainable effect of drying and disinfection operation. As a result, this study will be contributed to a successful example of climate-friendly cities while the World's urbanization level increased through sustainable steps taken.

Acknowledgment

This study is realized as bachelor's level research project of Chemical and Process Engineering in Bilecik Şeyh Edebali University, Also, thanks for their contributions these people are realized this study; Municipality of Bilecik, 144 th. Chief of Branch in General Directorate of Turkey Highways. Dogus Information Technology Co., Şemsettin Akağaç who is the Secretary of Engineering Faculty in Bilecik Şeyh Edebali University and Salim Kızılcık is the personnel of General Directorate of Construction in Bilecik Şeyh Edebali University.

Special Note

This study is realized as a bachelor's level research project for solving a specific problem. This study's conclusions as generating this manuscript, systems and methods intellectual and industrial rights related to legal studies are resuming.

5. REFERENCES

[1] Daniel Hoornweg and Perinaz Bhada-Tata., "WHAT A WASTE A Global Review of Solid Waste Management", No. 15 Urban Development & Local Government Unit World Bank, Report No 68135, March 2012.

[2] Palabıyık, H., Altunbaş, D., "Urban Solid Waste Management", Contemporary Approaches to Environmental Problems: Ecological, Economic, Political and Administrative Perspectives", C. Marin, U. Yıldırım (Ed.), Beta, İstanbul, 103-124, 2004,

[3] Armağan B., Demir İ., "GIS-Based Modeling of Municipal Solid Waste Collection System", İTÜ Mühendislik Dergisi, Cilt:4, Sayı:3, 119-125, 2005

[4] "Municipal Waste Statistics Survey of 2010" Statistical Institute of Turkey, TUİK 2010

[5] EPA, Environmental Protection Agency, "The Solid Waste Dilemma: An Agenda for Action", EPA, 330-SW-89-019, February 1989.

[6] Gary C. Young., "municipal solid waste to energy conversion processes" ABD, Wiley; 135-154, 2010.

[7] Koutchma, T., "Advances in ultraviolet light technology for non-thermal processing of liquid foods", Food Bioprocess Technol. 2: 138-155, 2009.

[8] Gouws, P.A., "Ultraviolet radiation as a nonthermal treatment for the inactivation of microorganisms in fruit juice", Innovat. Food Sci. Emerg. Technol. 9: 348-354, 2008.

[9] Tran, M.T.T., Farid, M. "Ultraviolet treatment of orange juices", Innovat. Food Sci. Emerg. Technol.5: 495-502, 2004.

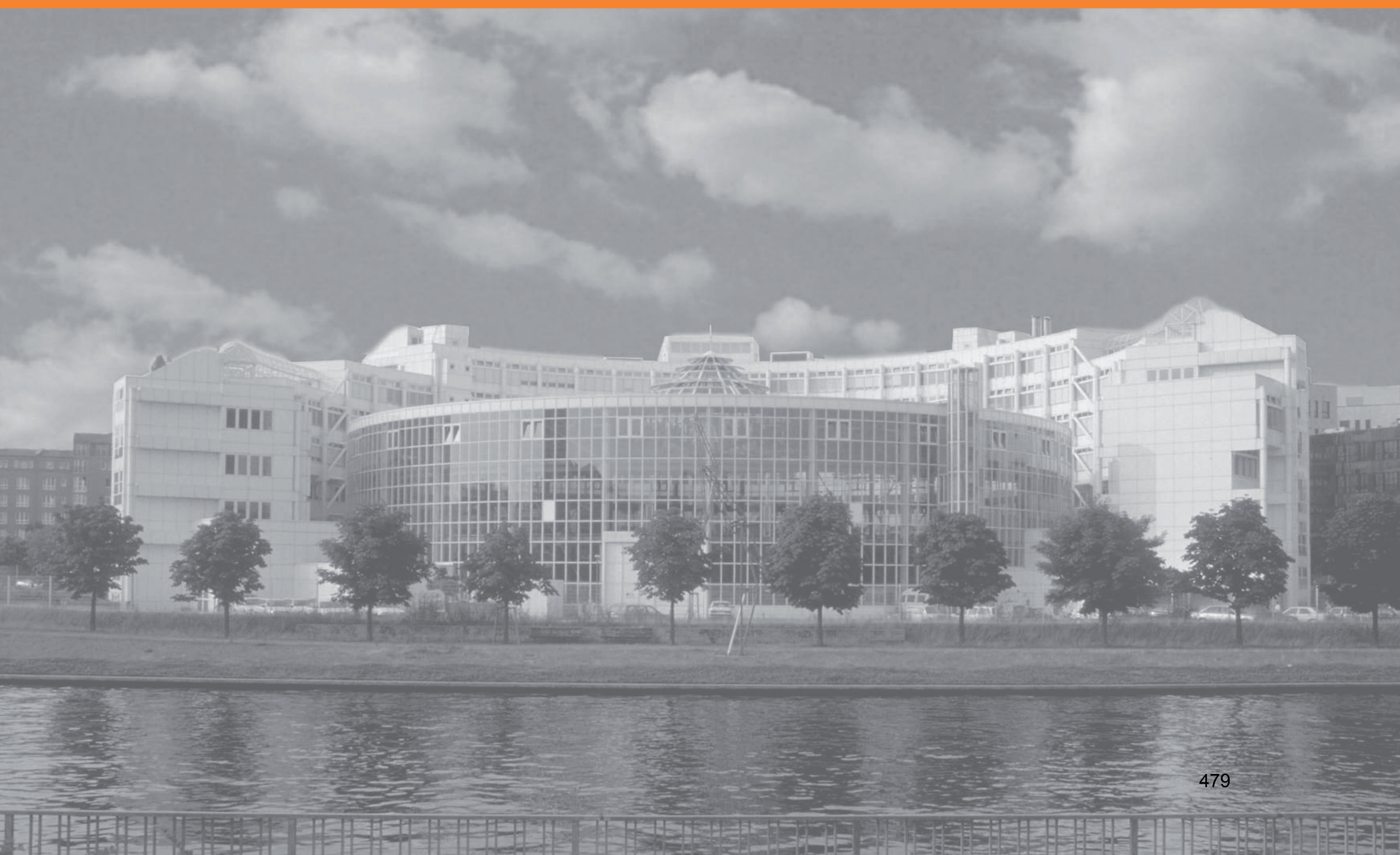
[10] Sizer, C.E., Balasubramaniam, V.M. "New intervention processes for minimally processed juices", Food Technol. 53(10): 64-67, 1999.

[11] Pereira, V.J., Weinberg, H.S., Linden, K.G., Singer, P.C., "UV degradation kinetics and modeling of pharmaceutical compounds in laboratory grade and surface water via direct and indirect photolysis at 254 nm", Environ. Sci. Technol. 41: 1682-1688, 2007.

[12] Mujumdar, A.S., "Handbook of Industrial Drying," Third Edition, Taylor & Francis Group, LLC, 2006.

[13] Kamil B. Varınca ve M. Talha Gönüllü., "A study on the method and Prevalence of Solar Energy Potential in Turkey, and the potentials", UGHEK2006, I. National Solar and Hydrogen Energy Congress Proceedings Book, ESOGÜ, Eskişehir/Turkey, 270-275, 2006.

Session 14
Supply Chain



GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

14.1 Environmental management practices within the supply chain: a case study of textile industry

H. C. D. Pimenta[1,2*], P. D. Ball [1], J. A. Aguiar [2], S. Evans [3]

[1] Manufacturing and Materials Department, Cranfield University, U.K

[2] Natural Resource Department, Federal Institute of Education, Science and Technology, Brazil

[3] Institute for Manufacturing, University of Cambridge, UK

Abstract

This study analysed the environmental management practices of a textile supply chain responsible for yarn manufacturing, located in Brazil. Using literature as the start point, a questionnaire was developed and applied with key individuals of the company. The results indicated the implementation of environmental tools, such as an environmental management system and the control of environmental aspects of the company, capable of contributing to the improvement of the company's environmental performance. It was also apparent that the environmental practices in the company studied were required for its suppliers, indicating a continuation of the environmental dimension along the supply chain. The relationship between the company and its partners indicates the existence of collaboration based on the joint development of technical and technological innovations and contribution to the improvement of training of employees.

Keywords:

Environmental management practices, Green supply chain management, Textile industry

1 INTRODUCTION

There is extensive use of water and energy to manufacture products in the textile sector [1]. Typically, there is also a huge production of wastewater in the dyeing process, characterized by a high level of chemical substances, such as heavy metals, dyes, detergents and suspended solids [2].

Not only the quality of materials supplied but also the commitment of each company membered of the supply chain in terms of a proper environmental adequacy will influence the environmental quality and performance of product in its lifecycle. According to Moore and Ausley [3], several industries depend on the resource and materials produced by textile sector; this means the greater the demand, the greater the consumption of resources for production. Thus, the impacts associated with this consumption, which is often exacerbated, can be seen in whole supply chain, since the water and energy usage is necessary at all levels of the production.

Cotton, for example, one of the main raw materials of the textile process, has worldwide impacts due to international distribution of the stages of both production and consumption [4]. Therefore, it is important that the members of textile supply chain adopt management tools which focus on the control of environmental impacts, reducing, for instance the waste of resource usage and pollution. For that, Vachon and Klassen [5] indicate the green supply chain as an option.

According to Simpson and Power [6], the environmental impacts related to SC member's activities might have negative effects in the whole supply chain, mainly the focal company (FC). The FC connects with both suppliers and customers, and makes decisions about the final manufactured product [7]. Any action of its suppliers that may directly or indirectly contradict the company's principles causes pressures from customers, non-governmental organizations (NGOs), and regulatory bodies. These pressure usually claim for guarantees of the SC memeber's previous proposed behavior [8] [9]. For instance, according to Seuring and Muller [10], some companies such as Nike, Levi Strauss, Disney, Adidas, Benetton and C&A had problems in the past due to their own and their suppliers' bad environmental and social conduct, including poor working conditions and environmental contamination.

Therefore, FC is held responsible for the environmental and social impacts that caused by their suppliers. Additionally, the focal company can be encouraged by the pressure exerted by the stakeholders previously mentioned, by internal or external factors. Internally, the motivations are characterized by costs reduction and productivity rise. External drivers are in turn related to the competitive advantage from the implementation of environmental tactics [11].

In this context, the green supply chain emerges as an alternative to manage pressure from different stakeholders. In accordance with Christopher [12], not only financial, material, and information management are pivotal elements of SCM, but there is also the environmental variable must be included through the cooperation between the SC member and FC [13].

The inclusion of environmental dimensions into the goals shared by the entire supply chain can improve the environmental performance of the all production process, from raw materials to the sale to consumers. According to , a mutual development of the supply chain members is started with the insertion of all the stages belonging to manufacture and commercialization of the product, which might enable to analyse of the overall impacts caused by the process and to design solutions to these impacts [8].

In this context, this study analyzed the environmental management practices with focus on the supply chain adopted by a textile industry responsible for yarn manufacturing, located in Brazil.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

The research presents initial considerations on a business model for sustainable supply chain management, which has been designed in partnership with the EPRSC Centre for Innovative Manufacturing in Industrial Sustainability <http://www.industrialsustainability.org/>.

In order to guide the proposed discussion, this paper is divided into four sections, in which the first brings the problem and the research objectives. Then the methodology used to collect and analyze data as well as the firm characterization where the case study was conducted, is presented. Finally, there are the results and discussion and the final considerations.

2 METHODOLOGY

2.1 Research Design

The data collection was carried out through semi-structured questionnaire, which was based on the literature review relating to reverse logistics and WEEE. The questionnaire contained two groups of variables, namely: "Environmental Management Function", "Environmental Practices" and "Interaction with Suppliers" (See, Table 1).

The first two groups aimed to analyze the company's internal situation; the first part evaluated the presence of an environmental management department and the professional responsible for the department. The second part analyzed the maturity level of the organization by checking the possible environmental management tactics adopted, also including the potential motivations and barriers faced by it in the decision process for selection of their particular practices.

The environmental management practices in the supply chain were analyzed from the point of view of the interaction of the company with its respective suppliers. Both the criteria used to select the suppliers and the environmental practices required of them by the industry studied were investigated and evaluated. Analysis of the data collected led to an evaluation of the level of maturity of the environmental management in the company. Also, it was possible to analyse the requirements adopted, and motivations and barriers considered at the time of its adoption as well as the interaction between company and suppliers.

Questions were answered by high management level supported by the sector responsible for environmental issues. The following answer scale was adopted: "no opinion", "never" (0-25% of application to reality of the company), "rarely" (26-50% of application to reality of the company); "almost always" (51-75% of application the reality of the company), and "always" (76-100% of application to reality of the company). The answers required were obtained from interviews with the director of operations and environmental manager of the studied company.

2.2 Firm Characterization

The company studied in this research is a multinational located in Rio Grande do Norte State (Northeast of Brazil), responsible for the production of around 128 types of yarn. The main raw materials used in the process are cotton or polyester fiber. It has 950 employees.

After the process, the material is transported to another factory in São Paulo (southeast of Brazil), for dyeing and subsequent sale to various branches. The main customers are clothes manufacture (62%) and leather industry for the manufacture of clothes, leather bags and shoes (17%) and automotive industry for the manufacture of seats and accessories (12%). Figure 1 illustrates the supply chain schematically.

The following materials are supplied to the study company: cotton fiber, polyester fiber; polyester continuous filament, nylon continuous filament; cardboard boxes; wooden pallets, and polyester film for packaging. These products account for about 98% of the inputs used in this case study.

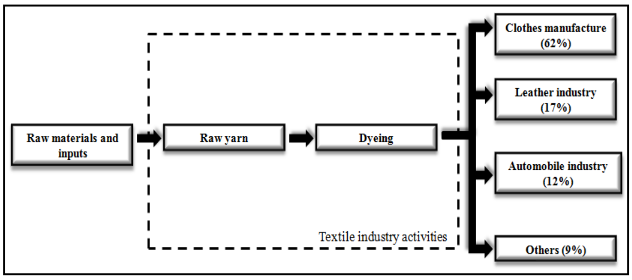


Figure 1: Supply chain – yarn production

The production process for yarn manufacturing is composed of 4 stages (Figure 2). The process begins with the quality control of raw material. The raw material is prepared by washing the cotton and removing undesired wastes (about 18% of the material is discarded after this step). The next step is the manufacture of the yarn through the spinning process. Finally, there is the twist of the yarn to obtain the line.

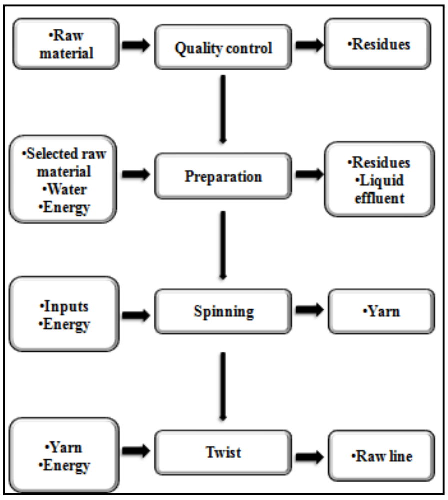


Figure 2: Flowchart– yarn production

3 RESULTS AND DISCUSSION

3.1 Environmental management of the studied company

The industry investigated had a specific department called "integrated management sector" to deal with environmental issues. This sector, which is managed by an engineer, also encompassed occupational health.

Figure 3 illustrates some environmental tactics/strategies adopted by the company studied, in terms of internal control, lifecycle view and quality program.

In terms of internal environmental control, it was claimed that the energy represents a significant impact in the company. In order to avoid an excessive consumption of electricity to maintain the factory regular functions, the company adopted an energy efficiency plan. This plan included a control and maintenance system to avoid peaks in the electricity used which had as a consequence high costs. Also, the machinery was preventively maintained and programed to work with efficiency around 85%. The plan also encompassed energy use awareness with focus on the proper use of electronic equipment.

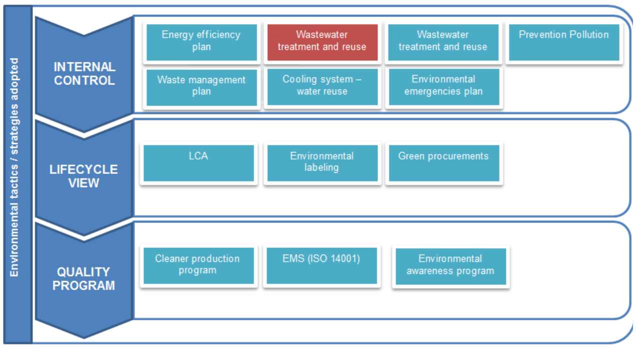


Figure 3: Supply chain – yarn production

In regard to water and wastewater control, it was stated that the water used in the cooling system was reused for gardening. The company had had a wastewater treatment for reuse, however, the system was disabled. Actually, it was requested by government (Public company of water and wastewater treatment) that the wastewater, which had a high level of nutrients due to the presence of natural cotton fibers, was released in the public industrial treatment system. This public system was based on biological treatment and the wastewater could be useful for this system.

In addition, it was reported that a waste management plan was properly implemented by the company studied. The waste plan included the correct transport and disposal of waste, with strategies to better manage the different types of waste and avoiding environmental impacts related to each individual type.

As this is a large company with continuous large-scale production, the risk of pollution and other environmental emergencies are imminent and need to be handled properly to avoid major consequences for the environment and the company's image. Hence, pollution prevention plans and plans for environmental emergencies are recognized by the company, as necessary. Both plans have focused on future fires and possible loss of products, with emphasis on air pollution and soil contamination. To achieve the goals related to the plans, the company has internal rules that stipulate, among other things, banning the burning of any material and flammable waste separation.

Concerning the lifecycle view, it was identified that Lifecycle assessment (LCA), environmental labeling and green procurements were implemented by company. Although, it was said by interviewees that LCA was implemented, they did not comment on which product was considered, the results achieved or even present a report.

The environmental labeling is related to the use of raw materials obtained with ecologically friendly procedures and recycling practiced during the manufacture of its products. Finally, the green procurement will be discussed in the next section.

With regard the quality program, Cleaner production (CP) was implemented to reduced wastes in some processes. According to Pimenta and Gouvinhas [14], CP might prevent continuously the waste and reduce the risk of operations for employees, community, and environment. Also, the company implemented Environmental Management System (EMS); however, it was not certificated by a third-party. It is important to note that to achieve a sustainable supply chain, the first step is for the company to follow the principles guided by ISO 14001 [8]. Moreover, Testa and Iraldo [9] indicate the existence of environmental management system as a first step for implementing a green supply chain. The absence of the proper certification was justified by the excessive bureaucracy found during the obtainment procedure.

In addition, to a quality program implemented by company, training and environmental awareness programmes were provided for its employees. Environmental awareness was focused on environmental issues related to the company operations in a continuous way. Training in turn focused on operational, occupational safety, "behavioral" and "occupational health". Training and environmental awareness are important to guarantee the effectiveness of the implemented practice. This is also pointed out by Sarkis et al. [15], whose research suggests there is a direct relationship between training effectiveness and the environmental practices adopted by the company, and the organizations analyzed in the research have only the adopted practices when the related training was effective.

Regarding the motivating factors for selection and application of current company environmental tactics, it was found that the most important was to comply with environmental law and the multinational standards. As a multinational firm, it could be seen that the company focused on compliance with regulatory bodies of the international market. This same motivation was observed in multinational companies which worked in China according to Zhu et al. [16]. Also, it was reported as a motivation, achievement of operational efficiency, and pursuit for innovations according to market trends. Schaltegger and Synnestvedt [17] claimed that giving attention to market trends related to environmental opportunities leads to economic opportunities, taking into account costs and benefits.

In addition, the search for operational efficiency is considered as a motivating factor as it indicates optimal use of resources and cost savings in the production process. One of the goals of the company is creating an improvement process aimed at reducing waste to zero, which will increase its efficiency.

Regarding the stakeholders, it was not stated that there was a strong pressure by suppliers or clients to change the company’s behavior. On the other hand, the organization itself demanded a positive environmental stance for suppliers.

Also, it was observed some barriers that hinder the adoption of environmental tactics by the company. The main barrier reported was the absence of government support. The study by Lee [13] for small and medium sized Korean companies concluded that there is significant influence from the government to adopt environmental practices as it facilitates the adoption by governmental investments. Thus, there may be no legal distinction between organizations that only fit to the regulatory standards and those who seek to go beyond and the use the environmental variable in a strategic way [18].

In general the company studied has a proactive stance to the environmental management, considering the classification system proposed by Jabour and Jabour [19]. This model classifies firms into three different levels: reactive (companies tackle environmental management as a way to meet the legislation), preventive (companies use it in different areas, but do not take it to a strategic level), and proactive (companies seek competitive advantages from the incorporation of environmental management in a strategic way). From the characteristics outlined by Pimenta [20], this classification is justified by the company's commitment through the adoption of different plans to address solutions to the possible impacts of its activities and the investments in training programs to raise its employee’s awareness in specific areas.

3.2 Environmental Management in the Supply Chain

Regarding the environmental selection criteria and partnership for improvements, it can be noted that for almost all evaluation criteria (See Table 2) the level of maturity was between "almost always" (51-75%) and "always" (76-100%) for the existence of demands made to suppliers in accordance with the environmental practices analyzed by the questionnaire. This result presents a certain level of concern by the company when selecting its suppliers so that they remain within the environmental targets previously established.

Among the criteria examined, it was noted that quality and price of the product is maintained as most important.

The company required an environmental management system from its suppliers

An environmental management system (ISO 14001) was required by company studied for its suppliers, but the certification of the system for a third-party did not apply to all cases. As previously discussed, requiring the ISO 14001 certification from suppliers is a simplification of the selection process [19]. It is necessary to include other practices that can be targeted to specific environmental problems. Only requiring the ISO 14001 may mean a low level of maturity of the environmental dimension. In the case of the company, other factors are required.

A second-party audit was conducted annually for all suppliers. This attitude considered by the organization as necessary to better understand the functioning of its partners. When audited, suppliers were also assessed on the existence of an "emergency and contingency plan" to manage emergencies and possible environmental impacts.

In addition, a life cycle assessment was demanded to assess whether the supplier complies with the requirements related to the product. Due to the costs associated with this analysis, the requirement was made only to large suppliers. The logistic department was responsible for selecting the companies, which would carry the LCA, and the department set criteria for the choice. The criteria were based on the characteristics of the raw material that was provided. If the inputs were strategic and difficult to replace, the company must conduct an LCA. The other companies are only audited.

As can be seen in Table 2, the LCA is required mostly to the supplier of cotton. Beamon [8] and Testa and Iraldo [9] state the importance of LCA for opportunities of cost reductions and replacing materials with more efficient ones. Nevertheless, it is very difficult to analyze an agricultural process and LCA can become more costly than expected, which does not benefit the supplier.

The company also practices activities considered by Simpson Power [6] as belonging to a collaborative relationship with suppliers through actions to support the development of suppliers, including training, technical and technological collaboration. The collaboration includes direct engagement between the various levels of the supply chain, in which the focal company commits itself to the improvement of its suppliers through employee training and environmental awareness, for example. In a general way, there was sharing of information and the company's commitment to improving the environmental performance of its partners. These attitudes were assessed by Simpson Power [6] as important to collaboration to the joint improvement of whole supply chain.

During the second-party audit, the presence of operational, occupational safety, environmental and occupational health training at the supplier’s factory were investigated. After the analysis of the quality of each type of training, the company would conduct new training those considered as ineffective in the audit. In general, the poor training was related to occupational safety and environmental management.

Environmental awareness through the supply chain was carried out by the training during the annual internal week of environmental awareness with key manager related to sustainability. Thus, the focal company could understand the individual vision of its partners on the importance of the environmental dimension. Also, the environmental management level of its suppliers could be improved when deficiencies were found.

Other collaboration activities conducted by the company were environmental emergency assistance and aid in the implementation of activities such as Cleaner Production Programmes and EMS. During the second-party audit, the main weakness was identified in order to closely work with the supplier to ensure that all important environmental aspects and impacts were well controlled.

The support for implementation of CP programmes and EMS (ISO 14001) was conducted by the company at its facilities through training. Managers from supplies were trained on the process of implementation and benefits of these environmental programmes.

Therefore, it can be note that not only the company requested some selection criteria for its suppliers but also helped to implement what was requested, in this case two environmental programmes (CP and EMS). According to Seuring and Muller [10], this relationship between requesting and support is essential to help suppliers to achieve the standards established by focal company.

Furthermore, the company also conducted technical and technological collaborations with its partners. One example was the development of new products necessary to the company, where both company and some suppliers share each other laboratorial procedures for improvements in materials and products standards.

Thus, it was found that all of the selection criteria were evidenced as practiced in the management routine of the company, being a documented procedure and a contractual clause.

From what has been discussed, it is considered that in addition to communicating with its suppliers, the company showed commitment to changing the environmental behavior of its partners. The company worked with its suppliers according to the previously cited classification of Simpson and Power [6] hence it can be noted some collaboration with suppliers in terms of training and technological sharing.

In general, it can be considered a limiting factor in this research the fact that much of the information analyzed was not validated or audited to confirm the information given. The access to documents and direct observation of the environment of the company and its suppliers would facilitate the understanding of the relationship and commitment of the entire supply chain regarding environmental variable.

Another limitation of this research was the focus on only one company, and the specific individual situation of this supply chain of textile production.

As the company adopts environmental practices and relates closely with its suppliers, the next step suggested here is to measure the environmental performance of the supply chain to assess the benefits conducted by the addition of the environmental variable.

Lastly, it is suggested a comparative study between this and other companies in the textile sector with similar positioning in the market is conducted to understand the competitive potential of the environmental variable, both nationally and internationally.

4 CONCLUSION

This paper focused on some selection criteria of suppliers and partnership intended to improve their environmental conduct adopted by a textile industry responsible for yarn manufacturing, located in Rio Grande do Norte (Brazil).

Regarding the practice of environmental management in the supply chain, it was found that the company studied works with its suppliers through collaboration, according to the classification of Simpson and Power [6]. Direct involvement activities confirm this positioning of the company, since it promotes training activities to improve the environmental performance of its partners, and collaborates in the development of the suppliers' initial weaknesses and works with them to develop products. Again, the company uses the environmental variable in a competitive way, including its suppliers in its strategic environmental approach.

The communication between the different levels of the supply chain was seen here as an essential factor for the joint development towards environmental improvement. Besides facilitating the design and development of the final product through discussion on price and quality of inputs, communication was also considered necessary to spread environmental responsibility, making it easier for suppliers to understand the environmental aspects of the stages of the production process and target solutions.

Therefore, to develop a sound partnership with suppliers, not only standards must be required, but also support must be given by focal company. This support will depend on, for example the number of members in the chain, also the number of tiers. There are a small number of suppliers in this study. This fact can explain the level of investment made and the control of the focal company studied in its supply chain, mainly conducted by audits.

5 REFERENCE

[1] Ren, X., 2000. Development of environmental performance indicators for textile process and product. Journal of Cleaner Production. 8, 473-481.

[2] Ciardelli, C., Ranieri, N., 2001. The treatment and reuse of wastewater in the textile industry by means of ozonation and electroflocculation. Water Research. 35, 2, 567-572.

[3] Moore, S.B., Ausley, L.W., 2004. Systems thinking and green chemistry in the textile industry: concepts, technlogies and benefits. Journal of Cleaner Production. 12, 585-601.

[4] Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., Gautam, R., 2006. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecological Economics. 60, 286-203.

[5] Vachon, S., Klassen, R. D., 2006. Extending green practices across the supply chain: The impact of upstream and downstream integration. International Journal of Operations & Production Management. 26, 7, 795-821.

[6] Simpson, D.F., Power,D.J., 2005. Use the supply relationship to develop lean and green suppliers. Supply Chain Management: an International Journal. v10, 1, 60-68.

[7] Lambert, D. M., Cooper, M. C., 2000. Issues in supply chain management. Industrial Marketing Management. 29, 65-83.

[8] Beamon, B. M., 1999. Designing the green supply chain. Logistics Information Management. 12, 332-342.

[9] Testa, F.; Iraldo, F., 2010. Shadows and lights of GSCM (Green Supply Chain Management): determinants and effects of these practices based on a multi-national study. Journal of Cleaner Production. 18, 953-962.

[10] Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. Journal of Cleaner Production. 16, 1699-1710.

[11] Rao, P., Holt, D., 2005. Do green supply chains lead to competitiveness and economic performance?. International Journal of Operations & Production Management. 25, 9, 898-916.

[12] Christopher, M., 2011. Logistics and supply chain management: creating value-adding networks. Pearson education.

[13] Lee, S., 2008. Drivers for the participation of small and medium-sized suppliers in green supply chain initiatives. Supply Chain Management: An International Journal. 13, 3, 185-198.

[14] Pimenta, H.C.P., Gouvinhas, R.P., 2012. A produção mais limpa como ferramenta da sustentabilidade empresarial: um estudo no estado do Rio Grande do Norte. Produção, 22, 3, 462-476.

[15] Sarkis, J., Gonzales-Torres, P., Adenso-Diaz, B., 2009. Stakeholder pressure and the adoption of environmental practices: the mediating effect of training. Journal of Operations Management. 163-176.

[16] Zhu, Q., Sarkis, J., Lai, K., 2007. Green supply chain management: pressures, practices and performance within the Chinese automobile industry. Journal of Cleaner Production. 15, 1041-1052.

[17] Schaltegger, S., Synnestvedt, T., 2002. The link between green and economic success: environmental management as the crucial trigger between environmental and economic performance. Journal of Environmental Management. 65, 339-346.

[18] Kagan, R. A., Thornton, D., Gunningham, N., 2003. Explaining corporate environmental performance: how does regulation matter?. Law & Society Review. 37, 1, 51-90.

[19] Jabour, A.B.L.S., Jabour, C.J.C., 2009. Are supplier selection criteria going green? Case studies of companies in Brazil. Industrial Management & Data Systems. 109, 4, 477-495.

[20] Pimenta, H.C.D., 2012. Gestão ambiental. Editora do Livro Técnico, 1 ed. Curitiba.

[21] Jabour, C.J.C., Santos, F.C.A., 2006. Evução da gestão ambiental na empresa: uma taxonmia integrada à gestão da produção e de recursos humans. Gestão e Produção. 13, 3, 435-448.

[22] Vastag, G., Kerekes, S., Rondinelli, D.A., 1996. Evaluation of corporate environmental management approaches: a framework and application. International Journal of Production Economics. 43, 193-211

[23] Berry, M.A., Rondinelli, D.A., 1998. Proactive corporate environmental management: A new industrial revolution. Academy of Management Executive. 12, 2, 38-50.

[24] Walker, H., Handfield, R. B.; Melnyk, S. A., 2008. Drivers and barriers to environmental supply chain management practices: Lessons from the public and private sectors. Journal of Purchasing & Supply Management. 14, 69–85.

[25] Hervani, A. A., Helms, M.M., Sarkis, J., 2005. Performance measurement for green supply chain management. Benchmarking: An International Journal, 12, 4, 330-353

[26] Srivastava, S K. 2007. Green supply-chain management: a state-of-the-art literature review. International Journal of Management Reviews. 9, 53-80.

[27] Walton, S.V., Handfield, R.B., Melnyk, S.A., 1998. The green supply chain: integrating suppliers into environmental management processes. International Journal of Purchasing and Materials Management. 2-11.

Table 1: Variables adopted in the questionnaire

Group of variables	Variables	Source
Environmental management sector	EM sector Existence	[15] [21]
	Professional responsible	
Environmental tactics	Implementation of EMS - 14001	[8] [9]
	*Internal control (*energy efficiency plan, waste management plan, wastewater treatment and reuse, environmental emergency plan, prevention pollution.); *Lifecycle view (*LCA, Environmental labeling and green procurement); *Quality (*EMS – ISO 14001, Cleaner production and training and environmental awareness)	[15] [22]
	Barriers to adoption of practices (Absence of requirements by law, government support, suppliers' pressure, customers' pressure, operational benefits and Low level of market trends focused on environmental management)	[13] [18]
	Motivations to adoption of practices (Compliance with legislation, Adequacy to the multinational standards ,Existence of government support, Suppliers' and custumers' pressure, Operational cost reduction, Operational efficiency and Innovations to meet market trends)	[16] [17] [23] [24]
Interaction with suppliers	Implementation of EMS - 14001	[9] [19]
	Environmental authorization from government	[25] [26]
	Environmental law compliance	
	EMS Tools (LCA, cleaner production, environmental control plan – waste, energy usage and pollution prevention, training and environmental awareness, internal and external recycling, second audit)	[5] [6] [8] [9] [10] [27]
	Cost and quality	[6]

Table 2: Selection criteria and demands made to suppliers about their environmental practices

Adoption of criteria/demands	Suppliers			
	Cotton lint	polyester fiber lint *	Cardboard boxes and wooden pallets	Polyester film for packing line
Product quality	A	A	A	A
Product price	A	A	A	A
Transporting costs	A	A	A	A
Preference for experienced companies	AA	A	AA	AA
Compliance with legislation	A	A	A	A
Environmental license	AA	A	A	A
Implemented EMS	A	A	A	A
EMS (ISO 14001)	AA	A	AA	AA
Cleaner production programs	AA	AA	AA	AA
Waste Management Plan	A	A	A	A
Energy Efficiency Plan	A	A	A	A
Prevention pollution plan	AA	A	A	A
LCA	A	AA	AA	AA
Internal recycling	R	A	A	A
External recycling	AA	A	A	A
Environmental performance assessment	R	AA	AA	AA
Sustainability reports	R	AA	AA	AA
Environmental labeling	AA	AA	AA	AA
Training programs with partners	AA	A	A	A
Environmental awareness activities with partners	AA	A	A	A
Audits of second party	A	A	A	A
Technical/technological collaborations	A	A	A	A
Assistance in environmental emergencies	A	AA	A	A
Assistance in program implementation (ISO, CP)	AA	AA	AA	AA
Rewards for behavior change	AA	AA	AA	AA

Legend: A: always; AA: almost always, R: rarely / * continuous filament polyester and continuous nylon filament

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

14.2 Gas cylinder distribution planning for saving the LP gas distributers

H. Fujikawa [1]

[1] School of Management, Tokyo University of Science, Japan

Abstract

There are two measures of distributing LP gas to residences in Japan. One is LP gas cylinder distribution method. Two gas cylinders are located in each residence. The other is municipal gas supply through underground pipelines. Recently latter took major market share due to the convenience of pipeline. Therefore LP gas distributers made their managerial situation worse and many companies disappeared from the gas distributer's market. However the Tohoku-earthquake showed the decisive shortcoming of underground pipeline. LP gas distribution measure needs to be re-examined for dealing with the emerging LP gas demand. Also it is necessary for LP gas distributers to decrease operating cost in order to survive. This study addresses minimizing inventory cost by decreasing the number of gas cylinders located in residences and minimizing transportation cost by ACO-based VRP. Gas cylinders requires natural resource and transportation of gas cylinders consumes much energy, too. Saving transportation operation may contribute to sustainable manufacturing.

Keywords:

Gas cylinder transportation, Ant Colony Optimization (ACO), Vehicle Routing Program (VRP), LP Gas distributer (Liquefied Petroleum gas)

1 INTRODUCTION

LP gas is one of the clean energies and indispensable to the life of the people. There are two ways of supplying LP gas to every residence or home. One is gas cylinder setting at home. The other is the manicipal gas distribution system. The municipal gas distribution system requires to lay piping underground. Once piping work has facilitated, there needs no additional treatement. As it must be convenient and economical for users, then the municipal gas system has widely spread in Japan. On the contrary, LP gas is supplied through gas cylinders distributed by the LP gas distributers. 2 gas cylinders are set for every residence.One cylinder is for use and additional cylinder is for run out present cylinder. Actually additional cylinders may not used. Namely one gas cylinder results to stay in each residence everytime as inventory. Gas distributers ask fee every month what each residence comsumed based upon the periodic gas quantity measurements. However the amount of gas staying in residence belongs to the inventory of gas distributers. So fundermentally, gas distributers have to hold surplus inventory due to this 2 cylinder system.

Recently, LP gas has been re-examined by the influence of the earthquake disaster in 2011. LP gas cylinder system has the feature that is robust against a disaster. This system shall not been influenced by crack in the ground occured by the earthquake since this system is not needed the supply line underground. In order to prepare disaster, LP gas providers are required, but they are facing managerial problems. So this paper addresses to improve productivity of LP gas providers to continue their performance and contribution to our living with coming disasters.

2 BACKGROUND

2.1 Japanese style LP gas distribution system

The municipal gas distribution system is very smart and efficient. Thanks to the urbanization, people living in urban area have increased. Then the municipal gas distribution system deprived share of gas supply from LP gas distributers. LP gas distributers' sales amount has declined from 2006 to 2010. Also the number of LP gas distributers (vertical axis) has declined that is described in Figure 1.

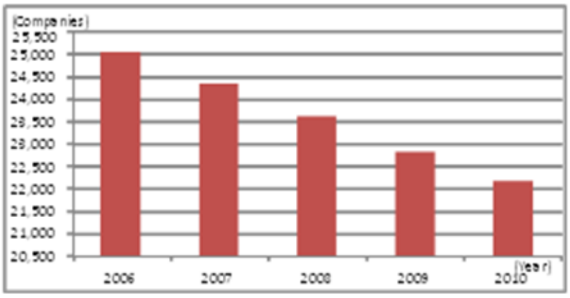


Figure 1: Changes the number of the LP gas distributers. [1]

Most important reason of this trend is high cost structure of the LP gas distributers. There locates two LP gas cylinders for every residence or home in local area of Japan. An additional cylinder is prepared for run out present cylinder. However LP gas held in the cylinders belongs to the LP Gas distributers as the inventory for sales. Therefore research [2] proposed to deprive additional cylinder in order to decrease inventory cost in spite of distribution cost increase shown in Figure 2. Research [2] decreases total cost which consists the sum of

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

inventory cost and transportation cost by decreasing one cylinder from each home.

Figure 2: Japanese style LP gas cylinder system.

2.2 Literature review

There are very few researches regarding gas cylinder transportation problem except [3]. Foltz et.all [3] addressed gas cylinder transportation problem in Hangarian company. Where the authors combine routing and scheduling problems. The problem has 7 filling stations and 2,400 sales points with minimizing transportaiton cost. They formulated 0-1 optimization problem and transformed into a linear optimizing problem by relaxing constraints. They finally configured software to apply actual business environment. Due to the difference of model and objectives, inventory cost is not considered in [3]. But this paper tries to tackle not only transportation cost but inventory cost which has been crutial manegerial aspect for Japanese LP gas distributers.

This paper succeeds research [2] with proposing distribution decision rule and developing ACO based VRP algorithm.

3 FORMULATION OF THE PROBLEM

3.1 LP Gas transportation Problem

As described above, LP gas distributers have faced business scale reduction. On the background of reduction, I have to specify some ineffective operations. One of them is double cylinder setting in each residence. This result is the problem of inventory cost for LP gas distributers. Present operation style is as follows: 2 cylinders are set in every home. Each home uses LP gas from the cylinder 1. If the cylinder 1 becomes empty, it will use from the cylinder 2. Meter is checked every month and present cylinder is replaced by the brought full-content cylinder whatever present home cylinder filled up. Then distributers convey heavy cylinders on the track every time. Let call this system as Model 1.

In order to decrease inventory, research [2] proposed model 1'. This model is as follows: 1 cylinder is set in every home. LP gas distributers know how much gas each home shall consume. Then no run out shall happen between periodic visits. On every visit, an insufficiency is added by the LP gas distributers with tanker or tank truck.

Research [2] calculates vehicle routing of above models by using saving method. The result is shown in Fig.3 below.

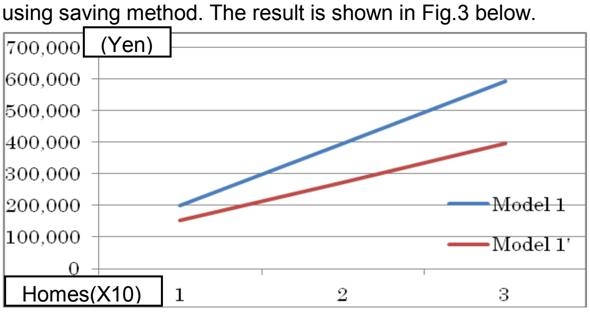


Figure 3: Result of cylinder decrease

It is validated that the decrease in additional cylinder can decrease total cost consisted by inventory cost and transportation cost. However, following remarks can be specified for further improvement.

1) Research [2] used saving method as a VRP, but there are more effective methods such as meta-heuristics.
2) As LP gas distributers knows each homes' consumption forecast, then it is not necessarily visit all homes.

Considering above hints below investigation shall be led.

3.2 Formulation

Objective function of this paper Z is described as follows:

$$MinZ = \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{K} X_{ijk} \times C_{ijk} \times D_{ij} + \sum_{t=1}^{T} \sum_{i=1}^{N} G_{it} \times B \quad (1)$$

$X_{ijk} = 1:$ A cylinder is delivered from home *i* to home *j* by track *k* (decision variable)

$X_{ijk} = 0:$ Otherwise

$C_{ijk}:$ Unit delivery cost from home *i* to home *j* by track *k*

$D_{ij}:$ Distance between home *i* to home *j*

$G_{it}:$ Inventory of cylinder of home *i* in period *t*

$B:$ Unit inventory cost of LP gas

$N:$ Number of home, index is *i*

$K:$ Number of track, index is *j*

$T:$ Number of period, index is *k*

First term of equation (1) is transportation cost and second term of that is inventory cost.

3.3 Approach

Based on the remarks in section 3.1, following actions shall be taken.

Research [2] could succeed to decrease total cost by depriving additional cylinders. Although a transportation cost is a slight increase, inventory cost down contributed to decline total cost down. It turned out that the further improvement can be pulled out by introducing an excellent VRP technique. So this paper adopts ACO based approach which has been reported good results especially routing problems [4], [5].

Another improvement view is usage of forecast data. Consumption of LP gas shall be the outcome of peoples' life style. Cooking time, bath time and winter time are typical gas consumption occasion. Quantity for each home shall be a function of the number of a family. LP Gas distributers are staying the position where such family information may collect. Therefore it can be concluded as a distribution rule for every month. That is 'It does not deliver, when the estimated month-end-stock exceeds a safety stock level'. This rule may transportation more efficient.

3.4 Distribution condition setting

Based upon the latter approach of previous section, a distribution condition shall be proposed. Information for each home can be known through the wireless communication control unit which attached to the gas meter.

If in-equation (2) is right in home *i*, LP gas distributer would visit home *i*.

$$G_{it+1} = G_{it} - \hat{U}_{it} \geq S_{it} \quad (2)$$

$\hat{U}_{it}$: Estimated consumption quantity of home *i* during period *t*

S_{it} : Safety inventory quantity of home *i* during period *t*

$$\hat{U}_{it} = \frac{\sum_{m=1}^{t-1} U_{im}}{(t-1)} \quad (3)$$

U_{im} : Actual gas consumption quantity of home *i* during period *m*

$$S_{it} = \alpha \times \sigma_i \times \sqrt{L_i} \quad (4)$$

α : Safety coefficient

σ_i : Standard deviation of gas consumption of home *i*

L_i : Lead time of distributing to home *i*

3.5 Development of VRP algorithm

The original idea of ACO(Ant Colony Optimization) comes from observing the exploitation of food resources among ants, in which ants' individually limited cognitive abilities have collectively been able to find the shortest path between a food source and the nest. It has been applied on a lot of optimization required scenes. Especially, ACO is well-utilized in the VRP or TSP problems as described in section 3.2 above. Because ants walking around seem to the researchers like agents moving in the simulated system. Flow of developed algorithm is shown in Fig.4.

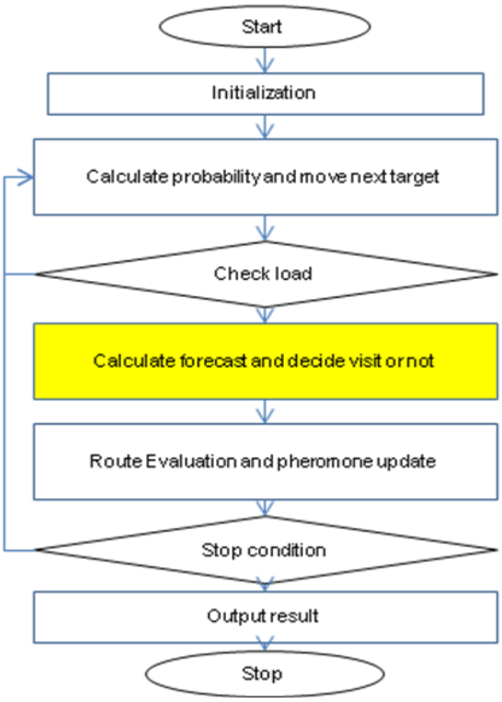


Figure 4: Flow of developed algorithm

Shaded box of the flow of the fig.4 is unique process in comparison with common ACO routine. This algorithm is coded by C++. Basic parameters of ACO have been tuned up through pre-experiments.

4 NUMERIC EXPERIMENT

4.1 Experiment setting

There are 2 steps and 5 models. Step-model relation is summarized below.

Step 1: Validate the effect of ACO based algorithm instead of saving method

Model 1 : 2 gas cylinders and every home visit (saving)

Model 1' : 1 gas cylinder and every home visit (saving)

Model 2 : 2 gas cylinders and every home visit (ACO)

Model 2' : 1 gas cylinder and every home visit (ACO) :

Step 2: Validate the effect of distribution condition introduction

Model 2' : 1 gas cylinder and every home visit (ACO)

Model 3 : 1 gas cylinder and selected home visit (ACO)

Evaluation of every experiment is done by total cost as described (1). Assumptions

Assumptions of the experiments

Following items are commonly set during whole experiments.

- Gas run out may not happen so no penalty cost set.
- If one cylinder would be vacant, the present cylinder shall be changed automatically. (Model 1 & Model 2)
- 10 tests shall be done for each models.
- Place of the homes are dispersed centering around the DC. Degree of disperse varies for 10 tests.
- Result data for each model is expressed as average of 10 test data.

4.2 Parameter Setting

The parameters used in experiments are set as follows :

- Weight of pheromone α = 1
- Weight of distance β = 1
- Pheromone remaining rate ρ =0.5
- Number of homes 10, 20, 30
- Number of aunts 100
- Transportation cost of track 100yen/km
- Transportation cost of tranker 500yen/km
- Inventory cost of gas cylinder 2,600yen/unit

4.3 Experiment result

Step 1: Validate the effect of ACO based algorithm instead of saving method.

In this step, effect of ACO technique introduction shall be checked. 2 cases are examined. These are Model 1 VS Model 2 and Model 1' VS Model 2'. Former comparison is summarized in figure 5. Latter comparison is summarized in figure 6. Vertical axis shows total cost in figure 5 and 6, transportation cost in figure 7 and 8.

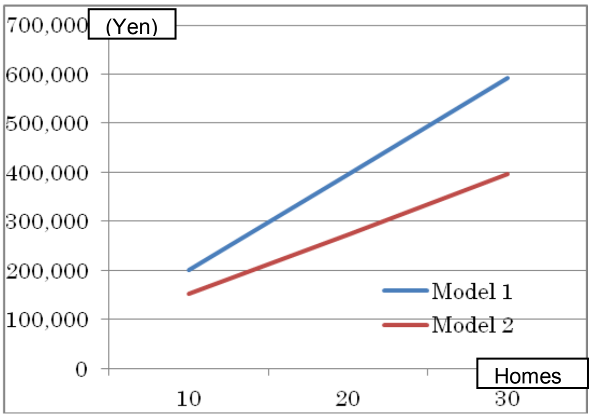


Figure 5: Total cost of Model 1 and Model 2

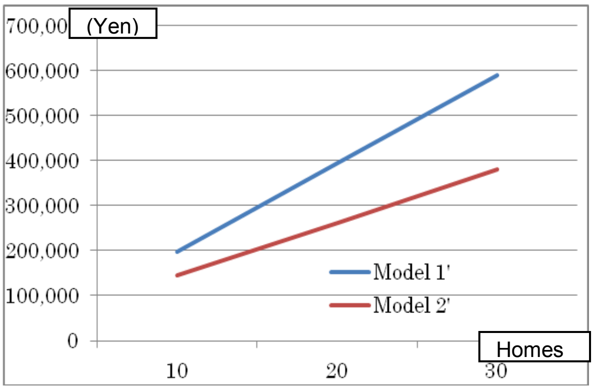


Figure 6: Total cost of Model 1’ and Model 2’

Both Figure 5 and 6 have same trend that is ACO provides lower cost solutions than saving method. Namely, Model 2 and Model 2’ are superior to Model 1 and Model 1’. In general, objective function generated by ACO-based VRP approach is lower than that by saving method. Trend of this result shows same way, whatever the number of homes is.

Step 2: Validate the effect of distribution condition introduction

Figure 7 shows distribution condition leads better results.

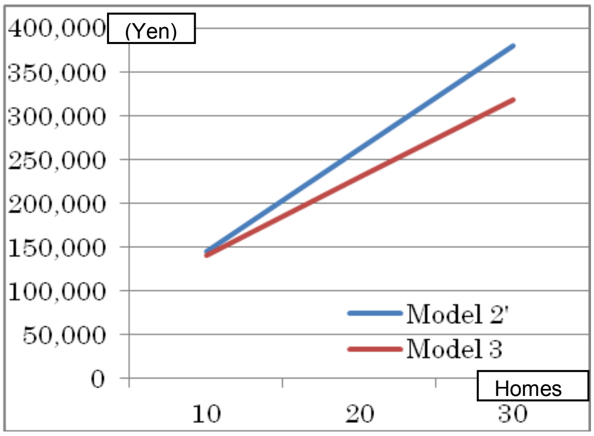


Figure 7: Total cost of Model 2’ and Model 3

As described in Figure 7, Model 3 generates lower total cost than that of Model 2’ in any number of homes. This means that number of visiting homes influences total cost. It is very natural. Transportation cost of step 2 is shown in Figure 8.

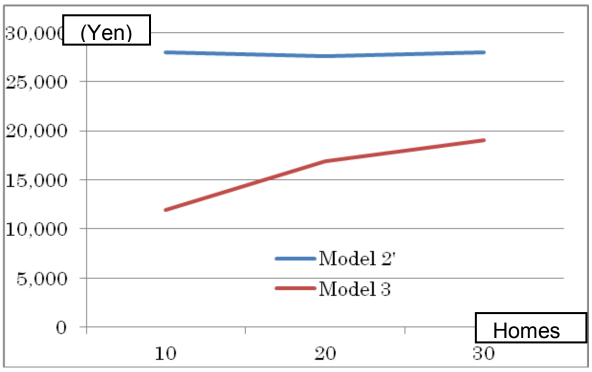


Figure 8: Transportation cost of Model 2’ and Model 3

Transportation cost of Model 3 is lower than that of Model 2’ in every number of homes. But transportation cost in Model 3 does not vary among the number of homes. Then inventory cost of Model 3 contributes total cost difference. Plotted value of Figure 8 is the average of ten experiments.

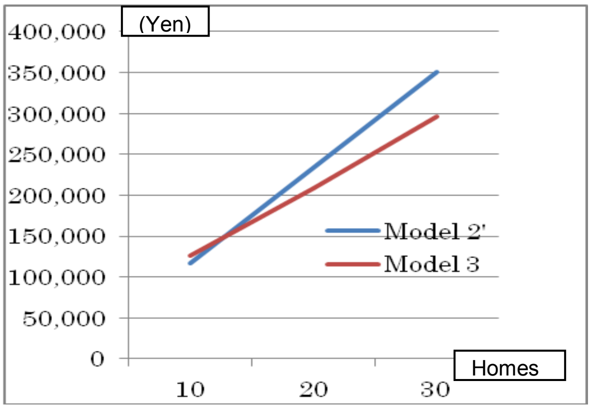


Figure 9: Inventory cost of Model 2’ and Model 3

As described above, inventory cost of Model 3 has same trend as total cost. That is because rate of inventory cost is larger than the rate of transportation cost. According to parameter setting of these experiments, total cost is highly influenced by the inventory cost due to the high weight versus transportation cost. Setting of cost data may decide the results of experiments.

In research [3], it was reduction of the total cost by drastic decrease in inventory cost, instead of slight increase in transportation cost. Through some experiments executed in this research, both cost of transportation and inventory cost could be reduced then the total cost was decreased.

5 CONCLUSION AND FUTURE STUDY

5.1 Conclusion

ACO based algorithm provides lower total cost VRP solutions in comparison with saving method. In previous study, total cost has decreased by dramatic inventory cost reduction and slight transportation cost increase. But with ACO based algorithm, both inventory and transportation costs have decreased.

5.2 Future study

This paper contains some unrealistic conditions such as no gas run out in experiment execution. These conditions should be diminished for the next study.

Model 3 needs forecast information that requires additional cost which has not considered in this paper. Information collection cost should be included under the name of the total cost.

6 ACKNOWLEDGMENTS

I extend my sincere thanks to Mr. H. Kaneko who contributed to preparing the experiments.

7 REFERENCES

[1] Japan gas energy home page.
http://www.j-gasenergy.co.jp/professional/toukei/index.php.

[2] Ishi, T., 2011, Applications of Spatial Data Structure, Addison-Wesley, Reading, MA.

[3] Foltz, F.,Meszaros, C., Rapcsak. T.,2005, Distribution of gas cylinders, European Journal of Operations Research, 87:613-623.

[4] Bell J. E., McMullen P. R., 2004, Ant colony optimization techniques for the vehicle routing problem, Advanced Engineering Informatics, 18-1 ; 41-48

[5] Yu B, Yang Z, Yao B., 2009, An improved ant colony optimization for vehicle routing problem, European Journal of Operational Research,196-1,171-176

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

14.3 Analysis a stochastic inventory control system under variability of semiconductor supply chain in automotive industry

Kenichi Nakashima[1] †, Thitima Sornmanapong[1], Hans Ehm[2], Geraldine Yachi[2]
[1]Department of Industrial Engineering and Management, Faculty of Engineering
Kanagawa University
[2]Infineon Technologies AG

Abstract

As an innovation in the semiconductor industry grows speedy, supply chain processes have not followed up. The variability in semiconductor supply chain have increased and been more complicated. These results in accurately forecast demand and set inventory target. Demand and supply are more and more stochastic and non-stationary. Inventory is one of the methods that companies are able to buffer themselves from complex and variable environment, while still being able to satisfy customer needs. We explore the variability of semiconductor industry in automotive industry. On the supply side, we evaluate variability in complexities of manufacturing process and also products are composed with multiple parts efforts to stochastic production lead-time. However in this paper, we disregard the variability arising from supply side so we assumed lead-time is fixed at 16 weeks. For demand side, the phenomenon is known as the bullwhip effect, the demand variability increases as one move up a supply chain, severely effects to semiconductor supply chain. This results the stochastic demand process is not well understood. Thus we evaluate the stochastic in demand as two aspects: 1) the dispersion of historical demand data from its mean which denoted as standard deviation of demand) 2) the difference between the actual demand and forecast data which denoted as standard deviation of forecast error. We use them as a proxy for demand variability. Then we apply the data to the base stock model. We then determine what each variability parameter contributes to inventory. The inventory model represents the semiconductor manufactory's inventory with actual data which provided from semiconductor company to calculate inventory target required to meet the desired customer service level.

Keywords:
inventory targets level, bullwhip effect, forecast error, demand fluctuation, base stock model

1 INTRODUCTION

Automotive industry has been undergoing a change with respect to the implementation of semiconductors into vehicles. Semiconductor technology has enabled many automotive systems manufactures to integrate various applications on a single chip by reducing the board area and optimizing performance. In the automotive semiconductor supply chain, relied upon by 1) several major semiconductor suppliers which we call it as Teir2nd 2) manufacturers who are responsible for delivery of the finished assembly which we call it as Teir1st 3) Original Equipment Manufacturer, OEM's. The suppliers' relation in automotive industry has made advance in significant evolution since Just-in-time or Lean production were discovered. The impact to SCM in the automotive industry is an efficient forming relationship with Teir1st and OEM's. Since Lean production absolutely relies on suppliers to have the right part at right place and at the right time. Once virtually all companies' information and knowledge are shared, both Teir1st and OEM's can have a full understanding to get the job done. Such a close relation between OEM's and Tier1st has had a substantial impact on Tier2nd. A successful information sharing has not been developed between Tier1st and Tier2nd results in a Tier2nd not being able to response to sudden and unpredictable requirements from Tier1st. Figure 1 shows the distinctive relationship among the semiconductor suppliers, Tier2nd, Teir1st and OEM's in automotive supply chain.

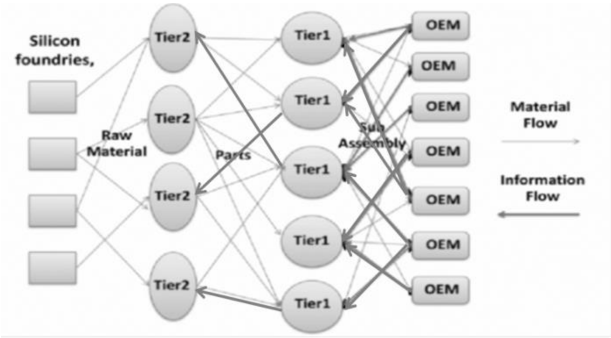


Figure 1: Automotive Suppliers' Relations

From the figure1, it can be noticed that information flow between Teir1st and OEM's is density while information flow between Teir1st and Tier2nd is slightly. This phenomenon has dramatic implication for Tier2nd's inventory management. Our analysis of supply chain variability focuses on semiconductor manufacturer in automotive industry. The paper organization is as follows: literature review and project description are mentioned in section2 then we analysis the variability in demand parameter in section3. In section 4 the base stock inventory model is described. In section 5 present the simulation inventory model. Finally, in section 6 the result and discussion the result from implement in section 5.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2 LITERATURE REVIEW AND PROJECT DESCRIPTION

2.1 Literature Review

There are many researches in the field of stochastic inventory management.

Graves[1] [2000] said safety stocks, is needed in a manufacturing system due to uncertainties in the requirements, production, and supply processes, and due to the inflexibility of the manufacturing system. They presented first the model for a single production stage and the model is a discrete-time model, in which events occur only at the start (or end) of a period. The focus of the research has been to decide how much inventory to keep between various production stages in order to provide. To set base stock level demand is an independent identically and normally-distributed random variable with mean μ and variance σ^2.

Neale[7] [2009] the base stock inventory model in his work. He uses the implications of the base-stock model by showing how yield variability can be incorporated.

Matthew and Willems[6] [2008] They used the forecast and actual demand history to calculate how the forecast deviates from the actual demand. These data was used for characterize μ and σ for define base stock.

Thomopoulos[8] [2006] gives a comparison between two fundamental methods of determining the safety stock. The methods are denoted as Availability and Service Level. The safety stock is the stock carried to meet the uncertainty associated with the forecasts of the demands. The uncertainty in demands is a measure of the forecast error.

2.2 Project Description

In this paper differs from the earlier work in terms of the comparing 2 approach for setting base stock level: 1) using data based on historical demand 2) using data based on forecasting error. Also this paper investigates the semiconductor's inventory management when company has specified forecast accuracy. This paper used forecast accuracy of 70% which was provided by semiconductor company. In the model, the production order releases are computed based on the forecasted demand adjustments for WIP discrepancy. Adjustments for inventory discrepancy depend on the approach as different types of standard deviation are utilized and desired service level. The rates of adjustments of these discrepancies are identified as the system control parameters. The service and cost performances of the system in terms of order fill rate.

3. ANALYSIS OF VARIABILITY IN SUPPLY CHAIN

In the semiconductor supply chain, the manufacturing organizations have completed variability analyses in order to understand and control process parameter with impact quality.

3.1 Variability Type

A key question to answer in advance of performing a statistical performing analysis in which type of variability that one wish to measure: natural variability or forecast variability. We define natural variability as historical variability of parameter in process or backward-looking. This type of variability is the variability of actual parameter results. For example, the past 3 months of the mean demand per month data are 900, 980, 1600. Such a measure might be appropriate if the distribution of actual demand over time is stationary. While, forecast variability is the variability that is referred by inaccurate forecasting or forecasting error. This type of variability is significant for non-station demand where mean is changing over time. To raise the question what is the primary indicator of process variability, the answer is depend on the assumption that the forecast is being used to make decision within a business. If so, and the core process is non-stationary, of course the forecast variability is an important contributor to the system. However, in this paper we consider on a stationary demand or the situation that we know the demand tendency while the forecast error also a significant contributor to overall system. In this case, historical variance probably might be able to be used to accurate predictor of future variance, whereas difference between forecasts and actual demand also be used as a proxy for variability. Then we quantify the contributions to variability from forecast error by taking the real forecast accuracy of semiconductor company. The metric that used to describe natural variability is the standard deviation of the distribution of the historical demand.

3.2 Coefficient of Variation, CV

In the both natural and forecast variability, the relative variability can be calculated by dividing standard deviation by mean value. Since the variability of parameter usually increases in proportion to its mean values, the coefficient of

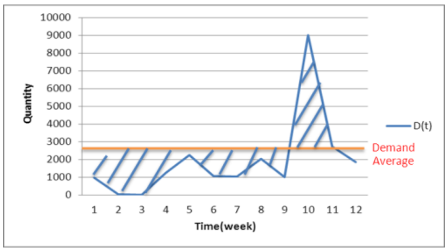


Figure 2: Natural Variability

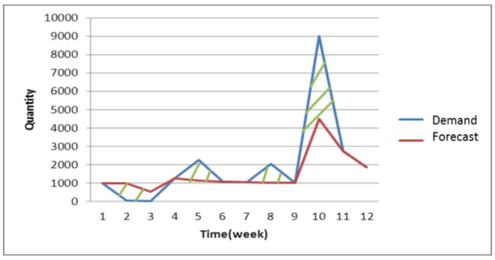


Figure 3: Forecast Variability

variation, CV is a way to compare across product. By scaling the variability to mean of actual demand, we use these values to model inventory of product with different coefficient of variation, CV from 0.3, 0.5 and 0.7. Low values, 0.3 is associated with stable customer demand, and a higher value, 0.7 is associated with unstable customer demand.

3.3. Variability Metrics-MPE and SMAPE

There are a significant number of forecast variability measurements. Some result in misleading summary statics. For example, MPE, Mean Percentage Error is an accuracy measure based on percentage errors.

$$MPE = 1/n \times \sum_{t=1}^{n} \frac{Forecast - Actual\ Demand}{Actual\ Demand}$$

Anyway, result from MPE can be skewed by large percentage error caused by small data scale and an effect of bias (see Appendix A). A measurement which mitigates the effect of outlier and bias is desirable. Symmetric mean absolute percentage error which called SMAPE. With $SMAPE_1$, the forecast bias is divided by the average of forecast and actual demand.

$$SMAPE_1 = 1/n \times \sum_{t=1}^{n} \frac{Abs(Forecast - Actual\ Demand)}{(Forecast + Actual\ Demand)/2}$$

The formula above provides a result between 0% and 200%. However a percentage error between 0% and 100% is much easier to interpret, then $SMAPE_2$ was introduced. But $SMAPE_2$ favors higher than actual forecast, It is not as symmetric as it sounds since over- and under-forecasts are not treated equally.

$$SMAPE_2 = 1/n \times \sum_{t=1}^{n} \frac{Abs(Forecast - Actual\ Demand)}{(Forecast + Actual\ Demand)}$$

However the MPE and $SMAPE_1$, $SMAPE_2$ are vulnerable to outliers and biases, it is an effective way to use $SMAPE_3$ whereby $SMAPE_3$ is more or less protected from outliers and biases.

$$SMAPE_3 = \sum_{t=1}^{n}(Forecast - Actual\ Demand) / \sum_{t=1}^{n}(Forecast + Actual\ Demand)$$

Since $SMAPE_3$ is protected against large errors caused by small scale data and can reduce the problem of upward bias, we use $SMAPE_3$ measurement in our work.

3.4 Variability in Forecasts

The forecast is generated by the industry experts in marketing section who use the combination of economic models, customer forecast, production capacities data, competitive information and intuition for generating forecast for different product. A significant contributor to any forecast error is called bias. Bias represents a consistent forecast error in the same direction (actual sales usually being above forecast or below forecast) over a period of time. The bias can be defined as under-forecasting and over-forecasting. Under-forecasting is a situation where the actual demand exceeds the forecast which we call SMAPE N, N%. Over-forecasting is a situation where actual demand is below the forecast which we call SMAPE P, P%. According to the real data from semiconductor company, it is interesting to note that forecasts for overall product are positively biased in all time horizons as shown below.

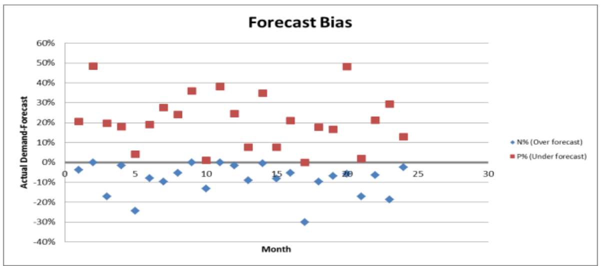


Figure 4: Bias of Forecasts

We may say that the forecast error is one of the significant parameter for doing business in semiconductor industry. Then we evaluated the variability of forecast error as a measure of the ability of forecast well which showed in figure 5.

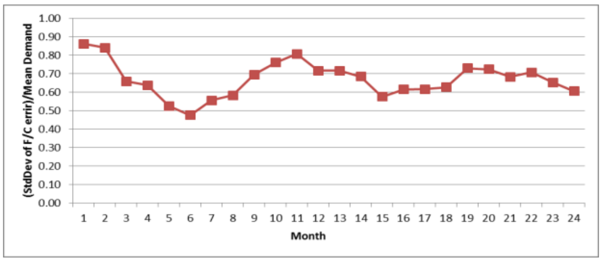


Figure 5: The variability of forecast error

The range of CV is from 0.5 to 0.9, we see that forecast are not quite a good demand signal.

3.5 Implication of Variability in Supply Chain

After considering the variability in semiconductor supply chain, it is quite common to say that semiconductor company's forecasting is bad. This raises the question that company should improve the forecast method to get the better forecasting data. However, to improve forecast accuracy in semiconductor industry is hard. The first reason that why improving forecast accuracy is hard is that there is high demand volatility. The volatility observed in the high-tech markets such as semiconductors often leads to high variability in business plan. Second, macroeconomic factors cause the shift in supply chain. This shift is known as the bullwhip effect, where variability gets amplified as the demand signal propagates up the supply chain [3]. Third, short semiconductor product lifecycles have little or no demand history, As a result, planning to customer-driven marketing forecasts was adequate. Forth, there are complex and complicated in the production process, which make supply forecasting required to meet demand is difficult. Sixth, the manufacturing is unable to quickly respond to forecast change due to long production lead time.

As the result of variability in supply chain, our suggestion is to modify the planning system to account for the inherent variability in existing process. The specific suggestion is present in the section 4.

4. STOCHASTIC INVENTORY MODEL

In this section, we discuss the model which composed of one production node and one inventory node. This model oversimplifies the supply chain and assumption about system which may not be perfectly accurate. However this model is more useful than some others model because it was implemented based on actual data about the average lead time or variability parameter. The suggestion resulting from this paper is that deciding the inventory target which can provide the better fill rate where

Fill rate = 1-(quantity of backorder/quantity of actual demand)

4.1 Base Stock Model

The primary assumption of model are priodic review, no set up cost, no lot sizing, infinite production capacity and net replenishment lead-time, LT is fix as 16 weeks according to actual data. In a basic inventory model, shown in Figure 6, an inventory is supplied by a production pipeline that has a constant lead time LT. Q(0; t] denotes the cumulative quantity of production ordered up to time t, and D(0; t] denotes the cumulative demand on the inventory up to time t. In this paper lead time is set as constant value. I(t) means on-hand Inventory level at the beginning of period t and is given by the following equation.

$$I(t) = Q(0, t - LT] - D(0, t] \qquad (1)$$

I(t) is allowed to be negative, so demand can be backorder. We will henceforth refer to I(t) as the on-hand inventory.

To proceed further, we need a model of how ordering takes place in response to demand. To define the policy, inventory position is introduced. The inventory position, IP (t), is defined as

$$IP(t) = I(t) + Q(t - LT, t] \qquad (2)$$

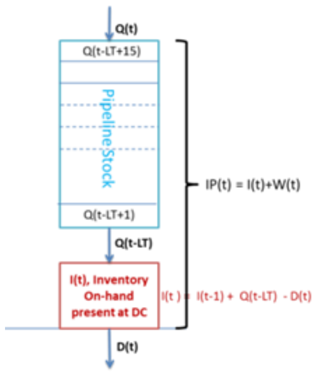


Figure 6: Diagram of Basic Inventory

where Q(t-LT, t] = Q(0, t] - Q(0,t-LT] is the total quantity ordered in the last 1 units of time, which is the total quantity in the pipeline that is due to arrive by time t + LT. When the production replenishes its inventory, the ordering quantities are always received after a constant lead time. An important fact to recognize is that we can regulate the inventory position by simply placing an order or by holding back orders. In other words, the inventory position is controllable [1].

$$I(t+LT) = Q(t-1, t] - D(t, t+LT] + I(t) \qquad (3)$$
$$= P(t) - D(t, t+LT]$$

So the on-hand inventory on lead-time in the future is the current inventory position minus the demand between now and time t + I. The term, D(t, t + LT], is the demand during lead time demand. Note that while P(t) is completely controllable, there is absolutely no control over the demand during lead time demand D(t, t+ LT]. All that can be done is to control the inventory position, P(t).

4.2 Base Stock Equation

Under this system, total inventory can be calculated to meet desired fill rate, whereas taking into account source of variability, the equation is shown below.

$$\text{Base Stock Level (BS)} = \mu_d \times (LT+r) + Z^{-1}(\alpha) \times \sigma_d \times (LT+r)^{1/2}$$

Where: μ_d = average demand over replenishment lead-time

r = review period

LT = replenishment lead-time

α = service level; probability of (not out of stock during the replenishment lead-time)

Z^{-1} = safety factor calculated from service level

σ_d = variability in demand

The pipeline stock or work in process is represented by the average demand time replenishment lead-time. The average demand time review period represent the cycle stock. In this work, we assume that average demand over review period is equal to production over review period. Thus, cycle stock is not related with analyzed variability, then we take it away from analysis. The last term in the equation refer to safety stock from variability, therefore we will focus on safety stock.

4.3 Safety Stock with Variability Demand

Safety stock is required to buffer from variability over replenishment lead-time. This can be calculated by determining the standard deviation of historical demand or standard deviation of forecast error. Variability in demand can be characterized as

1) Natural Variability; $\sigma_{\text{historical demand}} = \sum_{i=1}^{n}(Xi-\mu)^2/n$

2) Forecast Variability; $\sigma_{\text{F/C error}} = \sum_{i=1}^{n}(Fi-Di)^2/n$

To the canonical difference between the two type of variability, the resulted fill rate from the model based on natural variability and forecast variability is monitored, in the aspect of which one is an accurate predictor of future variance in different product.

4.4 Production Quantity Control

It is important for managers to realize that how they run items using Production Quantity Control which has a great impact on inventory. The production quantity should order to minimize the total inventory costs by balancing production cost, inventory holding cost and penalty cost (back order cost). By definition of adaptive base stock policy, where base stock is reset every month, production quantity, Q(t) is determined by following rule; where the inventory position, IP(t) in period t after demand fulfillment but before order placement, and D(t) represents the actual demand:

$$Q(t) = BS(t) - IP(t) \qquad (4); \quad \text{unit time is week}$$
$$= BS(t) - [BS(t-4) - D(t)]$$

With this production ordering process or sometime is called the order up-to model is a pull system because inventory is ordered in response to demand.

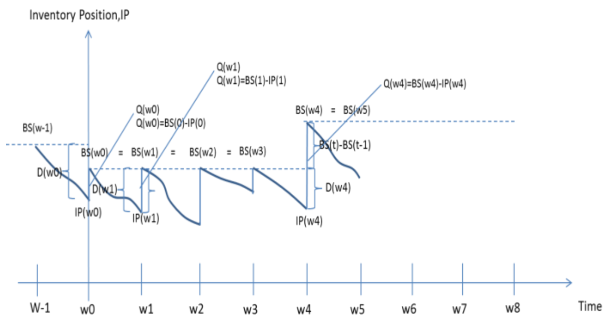


Figure 7: Production Ordering Policy.

5 INVENTORY SIMULATION MODEL

Here simulation model was developed based on the base stock model described in section 4 in Excel to simulate the performance of new base stock policy and verify an accurate predictor of future variance proposed in section 4.3.

5.1 Significant Parameters

Control parameter; α = Service Level (Available)

Condition input parameter; $\text{SMAPE3} = 30\%$

Condition output parameter; = Fill Rate

;where we observe the criteria when 2 options yield the same fill rate

Criteria; I(t) = Average Inventory On-hand

CV = coefficient of variance of demand

T = time horizon plan

n = repeat time

In this simulation, the time unit is week. The data of forecast accuracy which calculated be SMAPE_3 is based on real semiconductor company.

5.2 Simulate Process

i. Set α [75% , 99.99%]

ii. Generate n replications of Actual Demand(D) and Forecast(F) (see Appendix B)

iii. For each replication, compute
 1) the average Inventory On-Hand, $I_k=\sum_{i=1}^{T} I(t)j/T$
 2) Fill rate, , $\beta_k = 1 - (\sum_{i=1}^{T} \min[\text{I(t)j}, 0]/\sum_{i=1}^{T} D_j)$

iv. Estimate E[I] with $\sum_{k=1}^{n} Ik/n$
 Estimated E[β] with $\sum_{k=1}^{n} \beta k/n$

v. Repeat for different values of α

vi. Choose the E[I], estimate Inventory On-hand level that gives the same E[β], estimated fill rate from each approaches and compare E[I]

vii. run simulate with different product which categorized by difference CV

Simulate process can be presented in flow chart below.

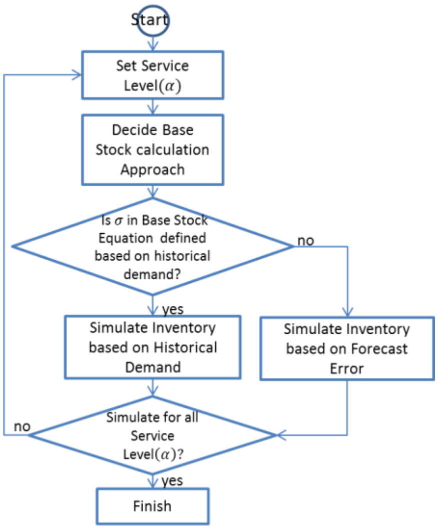


Figure 8: Simulation Flowchart for Inventory Model

6. RESULT AND DISCUSSION

This section presents the result of work done from single stage simulation experiment. First we present the variability in semiconductor supply chain within which to understand the impact of variability on process. With an understandind of variability inherent in the system, we can begin to simplify analyses by using less variability data. Once variability in system has been measure, we will be able to avoid more variable data. Therefore, we compared 2 approach; 1) using data based on historical demand 2) using data based on forecasting error for setting base stock level. We utilized the real data to establish relationships between variability and inventory requirement. Based on the evaluated of data and scenarios, the simulation is shown as figure below.

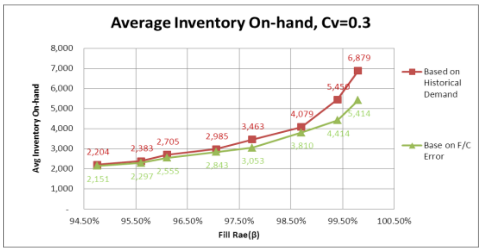


Figure 9: Better contributor in demand variability, CV of 0.3

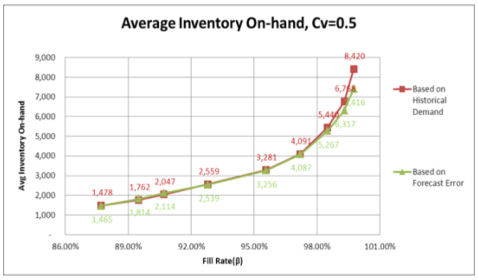


Figure 10: Better contributor in demand variability, CV of 0.5

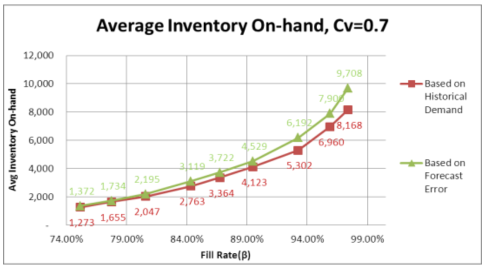


Figure 11: Better contributor in demand variability, CV of 0.7

From the resulted graph, X-axis is average inventory on-hand and Y-axis is fill rate. We observed when 2 approaches yield the same fill rate, the approach that can provide the lower average inventory on-hand is advantage. In this paper, under the situation of low accuracy of 70% and under-forecast is over over-forecast, product which has stable demand performance (CV=0.3), forecast error data, forecast variability is used as a proxy for variability. For product which has unstable demand performance (CV=0.7), historical demand data, natural variability is used as a proxy for variability. This is because when demand fluctuated a lot, forecast is more inaccurate so it is not able to be a trace for control inventory, then using historical demand is better. With this result, company can link related variability to improve the demand-supply system in order to archive the required fill rate (delivery performance). However, this paper needs to develop and extend to be more complexity. Follow-on research should include the development a model to ramp-up period.

ACKNOWLEDGEMENT

This research is supported in part by JSPS Grants-in- Aid for Scientific Research No. 23510193.

REFERENCES

[1] Graves S & Willems S. 2000, Optimizing Strategic Safety Stock Placement in Supply Chains. Manufacturing & Service Operations Management Vol. 2, No. 1, Winter 2000, pp. 68–83

[2] Guillermo G. & Garrett J. 1994, Optimal Dynamic Pricing of Inventories with Stochastic Demand over Finite MANAGEMENT SCIENCE/Vol. 40, No. 8, pp.999-1019

[3] Hans E., 2012, The Bullwhip Effect Anylogic Conference Supply Chain Innovation, Berlin, Germany, AnyLogic Conference 2012, www.anylogic.com/alc-2012

[4] Kojima. M and Nakashima. K and Ohno. K., 2008, “Performance Evaluation of SCM in JIT envi-ronment”. International Journal of Production Economics Vol.115, No.2, pp 439-443.

[5] Marshall L. Fisher and Janice H. Hammond., 1994, Making Supply Meet Demand in an Uncertain World, Harvard Business Review, Vol. 94302, pp83-93

[6] Matthew P-M, Sean P-W 2008, Setting Safety-Stock Targets at Intel in the Presence of Forecast Bias,. Management Science, 38/2 112–122

[7] Neal J & Willems S. 2009, Managing Inventory in Supply Chains with Nonstationary Demand, Interfaces Vol. 39, No. 5, pp. 388–399

[8] Thomopoulos N. 2006, Safety Stock comparison with Availability and Service level, The International Applied Business Research (IABR) Conference in Cancun, Mexico -- March 20 - 24, 2006

Appendix A- Outlier and Bounded in MAPE, $SMAPE_1$ and $SMAPE_2$

Case1: MPE is skewed by large percentage error caused by small data scale.

	Forecast	Actual Demand	$(F_t-D_t)/D_t$
SKU 1	2	4	50%
SKU 2	58	50	16%
SKU 3	50	50	0%
SKU 4	42	50	-16%
SKU 5	48	50	-4%
MPE			-11%
MPE (exclude SKU 1)			-1%

MPE and MPE (exclude small data, SKU1) give quite different result.

Case2: $SMAPE_1$ and $SMAPE_2$ are vulnerable to outliers and biases.

	Forecast	Actual Demand	$\|(D_t - F_t)\| / (D_t+F_t)/2$	$\|(D_t - F_t)\| / (D_t+F_t)$
SKU 1	50	200	120%	60%
SKU 2	50	200	200%	100%
SKU 3	50	150	100%	50%
SKU 4	60	50	18%	9%
SKU 5	40	50	22%	11%
SMAPE 1			92%	
SMAPE 2				46%

The error of $SMAP_1$ in SKU1,SKU2 and SKU3 are bounded by -200% to 200%, which a percentage error between 0% and 100% is much easier to interpret, while the error of $SMAPE_2$ in SKU4 and SKU5 favors higher than actual forecast.

Appendix B- Generate Demand data and Forecast data under the condition of having 70% forecast accuracy calculated by $SMAPE_3$

Let:

D_i = demand data
F_i = Forecast data

p_i = probability

x_5 = median = mean

Analyzing :

i. when the actual demand is lower than its mean, there is a high probability of over-forecast event (Forecast > Actual demand)
ii. when the actual demand is higher than its mean, there is a high probability of under-forecast event (Forecast < Actual demand)

i	D_i	F_i	p_i	$\|D_i-F_i\|$	$p_i(D_i-F_i)$	$p_i(D_i+F_i)$
1	x_1	$f_1=ax_1$	p_1	$x_1- ax_1$	p_1 (a-1) x_1	p_1 (1+a) x_1
2	x_2	$f_2=ax_2$	p_2	$x_2- ax_2$	p_2 (a-1) x_2	p_2 (1+a) x_2
3	x_3	$f_3=ax_3$	p_3	$x_3- ax_3$	p_3 (a-1) x_3	p_3 (1+a) x_3
4	x_4	$f_4=ax_4$	p_4	$x_4- ax_4$	p_4 (a-1) x_4	p_4 (1+a) x_4
5	x_5	$f_5=x_5$	p_5	$x_5- x_5$	p_5 (0)	p_5 (0)
6	x_6	$f_6=bx_6$	p_6	$x_6- bx_6$	p_6 (1- b) x_6	p_6 (1+ b) x_6
7	x_7	$f_7=bx_7$	p_7	$x_7- bx_7$	p_7 (1- b) x_7	p_7 (1+ b) x_7
8	x_8	$f_8=bx_8$	p_8	$x_8- bx_8$	p_8 (1- b) x_8	p_8 (1+ b) x_8
9	x_9	$f_9=bx_9$	p_9	$x_9- bx_9$	p_9 (1- b) x_9	p_9 (1+ b) x_9

Assuming: Forecast Accuracy = 70%, Over-forecasting = 10%

Equation: At Forecast Accuracy of 70%

$$E[SMAPE] = E[(\sum|D-F|)/\sum(D+F)] = 0.3 \qquad (1)$$

$$[(a-1)\sum_{i=1}^{i=4} PiXi + (1-b)\sum_{i=6}^{i=9} PiXi]/\sum_{i=1}^{i=9}(Di + Fi)] = 0.3$$

Over-Forecasting = 10%, which means Under-forecast = 20%

$$\{(a-1)\sum_{i=1}^{i=4} PiXi\}/\sum_{i=1}^{i=9}(Di + Fi) = 0.1 \qquad (2)$$

$$\{(1-b)\sum_{i=6}^{i=9} PiXi\}/\sum_{i=1}^{i=9}(Di + Fi) = 0.2 \qquad (3)$$

Generate the demand data from $x_1$to x_9, and the forecast data from f_1 to f_9 where let the x_5 is median. Then find a and b from equation 2 and 3. Result is…

$$a = 152\%$$

$$b = 34\ \%$$

By scaling the variability to mean of actual demand, we use these values to model inventory of product with different coefficient of variation, CV from 0.3, 0.5 and 0.7, where CV of demand is set as follow

CV = Standard Deviation / mean

$$= [(D_i-\overline{D})^2/n]^{1/2}/[\sum(D_i \times p_i)/n]$$

14.4 The level of organizational integration framework

Zahra Lotfi , Muriati Mukhtar , Shahnorbanun Sahran and Ali Taei Zadeh

School of Information Technology, Faculty of Information Science and Technology, Universiti Kebangsaan

Abstract
In today's global economy, it is critical for companies to improve their competitive advantages. Supply chain integration, if applied effectively, is known to bring about a significant improvement to all companies. The target of supply chain integration is to enhance the material and information flows within a company and also connect it with other supply chain members. With the technology available today, very intimate, beneficial and profitable supply chain integrations can be structured. Many researches have been conducted which approve a much higher operational and business performance of firms while the level of integration raises. The purpose of this study is to provide an overview of the level of supply chain integration frameworks in the manufacturing sector of the supply chain management and to derive a proposed framework from this overview. As a result, a proposed framework for supply chain members has been elaborated.

Keywords:
Supply chain integration (SCI); Supply chain management (SCM); Level of supply chain integration; Framework; Manufacturing sector

1. INTRODUCTION

In order to survive and compete in today's worldwide market, manufacturing sector strongly needs to create, share and disseminate up-to-date and appropriate knowledge and information [1] and one of the competitive advantages of today is found to be supply chain integration where the goal is to make the best use of material and date flow internally through the center of the company and also externally through supply chain industries [2].

For competitive advantages, many companies have now focused more on their supply chains and hence have thought of ways to improve their supply chain management and the ability to manage the supply chain effectively is now very critical to any company that wants to compete with others.

To be able to compete powerfully, companies need to know everything about the other competitors and to identify areas of possible competitive advantage, they need to compare their products continuously to those of the other competitive companies [3]. The goal of supply chain management is to simply upgrade the competitive performance by improving the integration in the company, starting with internal integration and then linking it with the external functions of all channel members such as, suppliers and customers [4].

A supply chain can be described as a series of organizations that may be involved in different processes and activities to produce products and services for ultimate customers, both upstream and downstream. A supply chain, therefore, is made up of a number of companies including suppliers, distributions and the end-customers. Stadtler [5] defines Supply Chain Management (SCM) as, the act of sharing material, information and financial information within organizational units, so as to meet customer' needs and as a result, enhance the entire supply chain involved. The creation of value for the end customers and organizations involved in the supply chain network is simply the final goal of supply chain management [6]. To fulfill this, the administrations in the supply chain must integrate their activities both internally and also externally with their customers and suppliers [2] .

Supply Chain integration is an important necessity of successful product development. To form a significant component of supply chain integration, customer and supplier integrations need to assemble on an internal integration controlled by the manufacturer.

Zhao's study proved that for integrating with firms' consumers and suppliers, there is a primal need for improvement in the internal ability, which makes the internal integration a necessity for enabling external integration [7]. Many studies prove that with the increase in the level of integration of a company, the level of business performances increases too [8, 9].

It is clear that for getting more integration in supply chains need to integrate internally in a first step and then integrate externally with suppliers and customers to get fully integrated into the supply chain.

To illustrate the level of supply chain integration in the manufacturing sector, we perceive three important dimensions of supply chain integration specifically internal integration, supplier integration and customer integration. in this study we construct an overview supply chain integration and level of organizational integration and then we proposed a framework to investigate the overall level of organizational integration in the supply chain. This proposed framework will validate in the next study.

2. LITERATURE REVIEW AND PROPOSED FRAMEWORK

2.1. Supply Chain Integration

The subject of many important debates and discussions among the academia is supply chain integration (e.g. [8, 10-14]. Seamless supply chain initiates from a systems perspective [6], where the efficiency of the entire obtains further performance than a field effective sub-systems. The debate is, if integration based on shared information, would lead to trade-offs and wide ranging decisions or not [8, 15, 16]. Therefore, current research should give more importance to the supply chain integration.

With the technology available today, different network structures can be modeled to make the coordination and integration within supply chain partners even more intimate. This partnership leads to a more beneficial and profitable

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

supply chain. There will be an increase in information flows, a reduction in the uncertainty and the ultimate customers will receive higher quality products with lesser costs in a shorter period of time [17].

The advantages of an integrated supply chain can be seen through the high productivity of the links between many different supply chain activities, and those links should be prone to the high productivity of building and utilizing of different supply chain practices. This in simpler words suggests that a company pursuing the high productivity of SCM practices must give loads of consideration to SC integration. SCM practices containing internal between functional integration within a company and external integration with suppliers or customers, can be implemented to achieve a successful and improved supply chain performance [18, 19].

Interaction of different members in a supply chain is highly recommended for individual supply chain practices cannot improve their private efficiency and effectiveness [4]. However, this recommended interaction has been, only recently, through the advancement in Information Technology become practical [20].

Supply Chain Integration (SCI) can be defined by the amount of collaboration between a manufacturer and its supply chain partners as well as the degree to which a manufacturer conducts intra- and inter-organizational processes [21]. In this study we distinguish one of aspect of integration that is the level of supply chain integration.

2.2. Level of Supply chain Integration

Many studies have been conducted, proving that as the level of integration used in a firm increases, so do the operational and business performance of the firm [8, 9].

The level of supply chain integration can be found by considering the number of activities within a dimension of the firm. This level can be increased by making use of advanced practices. Some articles offer useful descriptions and frameworks to evaluate the level of supply chain integration. An overview of a few of these articles is provided in Table 1.

Table 1: Some levels of integration classification.

Name & Source	**Level of integration classification**
Stevens Model [11]	• Stage I: the fragmented operations within the individual company • Stage II: limited integration between adjacent functions (such as: purchasing and materials control) • Stage III : required the internal integration of the end-to-end planning in the individual company , and • Stage IV: the true supply chain integration including upstream to suppliers and downstream to customers.
Supply Chain Operations Reference (SCOR) [12]	• Top Level (process types) • Configuration Level (process categories) • Process Element Level (decompose processes) • Implementation Level (decompose process elements)
Metz Model [13]	• Phase 1: 2 functions SC include : Transportation and Warehousing • Phase 2: 5 functions SC: 2 Functions of Phase1 plus 3 more functions include: Manufacturing; Procurement and Order management • Phase 3: 7 functions SC: 5 Functions of Phase1 and 2 plus 2 more functions include: Suppliers and Customers • Phase 4: 10 functions SC: 7 Functions of Phase1, 2 and 3 plus 3 more functions include: Product development; Marketing and Customer service
Frohlich and Westbrook Model [8]	• Inward-facing, • Periphery-facing, • Supplier-facing, • Customer-facing, and • Outward-facing
Frohlich and Westbrook Model [14]	• Model A: Web-based Low Integration • Model B: Web-based Supply Integration • Model C: Web-based Demand Integration • Model D: Web-based Demand Chain Management Integration
Bagchi and Skjøtt-Larsen Model [22]	• Low • Medium • High

Stevens' Model

Stevens [11] identified supply chain integration in four stages including:

Stage 1: the separated operations enclosed by the individual company from purchasing to distribution

Stage 2: Limited Functional integration including material and manufacturing management and distribution

Stage 3: The planning of the internal integration enclosed by the individual company

Stage 4: The planning of the external integration including the suppliers, internal supply chain and customers

Stevens' Model describes the steps factories and industries go through while expanding over time in terms of their integration, such as a first starting with internal integration and then going on to external integration. His model's framework is made of of 4 stages of integration in a company. Starting with the first stage at which the larger parts of the industry are separated and have to carry out functions individually and are responsible for their own activities, such as sales and distribution, this would cause isolated optimization. The second stage focuses on the internal flow of products in the factory. This will require only a limited amount of integration between neighboring functions, such as materials management and manufacturing management. The main plan here is to cut costs which will lower quality of performance. The orders from customers will then be forwarded which will cause poor appearance of real customer demand, which will result in inadequate planning and non essentials buffering of stocks between the different available units. At the third stage, the company has an advanced internal integration at which each function's integration is managed directly by the company and no longer by the individual units. The last stage is where the external integration is advanced and the full supply chain integration is achieved. Now the company's integration starts from the suppliers all the way to the customers.

Supply Chain Operations Reference (SCOR) Model (1996)

SCOR is a framework introduced to evaluate and enhance enterprises' supply chain performance and management . Supply Chain Council defines SCOR as follows:

> "The SCOR model provides a unique framework that links business process, metrics, best practices and technology features into a unified structure to support communication among supply chain partners and to improve the effectiveness of supply chain management and related supply chain improvement activities."

SCOR consists of four levels which are based on a source, make, deliver the framework. The first level, being the top level, outlines the purpose of the SCOR model and defines the foundation for competitive performance goals. The second level, also known as configuration level, is where firms implement their operational strategies according to the configurations they select for their supply chains. The third level, also called process element level, determines a firm's capability to challenge successfully and hence contains inputs, outputs, and flows of each transaction element. The fourth and last level of this model describes the implementation of specific supply chain practices. This model illustrates level one as the lowest level of integration and level four as the highest level of integration [12].

Metz's Model

Metz [13] represented the evolution of SCM from its origin to the current in a four development process phases.

Phase1: include two functions of supply chain: Transportation and Warehousing

Phase2: include five functions of the supply chain: Transportation, Warehousing, Manufacturing; Procurement and Order management

Phase3: include seven functions of the supply chain: Transportation, Warehousing, Manufacturing; Procurement, Order management, Suppliers and Customers

Phase4: include ten functions of the supply chain: Transportation, Warehousing, Manufacturing; Procurement, Order management, Suppliers, Customers, Product development, Marketing and Customer service

Metz's Model clearly shows the steady advancement of the supply chain. The rapid development of information technology (IT) can be applied to raise the supply chain, as more functions can be added into the total process. This advancement in IT allows more information to travel more quickly and accurately along the supply chains, providing integration between the trading partners. An integrated supply chain may result in supreme chain performance and progress competitive advantages for all the parties implicated. Therefore many firms have considered SCM as a top priority.

Frohlich and Westbrook Model

Frohlich and Westbrook [8] inspected customer and supplier integration tactics in the manufacturing sector all over the world. This inspection led to the development of scales measuring supply chain integration with the recognition of five alternatives. Frohlich and Westbrook's model can assist the effectively of supply chain integration. The minimum integrated is named "inward-facing" while the most integrated is called "outward-facing". They use quartiles to explain their model. The five alternative arcs of supply chain integration identified by this model are:

Inward-facing: In lower quartile for suppliers, and in the lower quartile for customers.

Periphery-facing: Above lower quartile for suppliers or customers, but below upper quartile for suppliers and customers.

Supplier-facing: In the upper quartile for suppliers, and below upper quartile for customers.

Customer-facing: In the upper quartile for customers, and below upper quartile for suppliers.

Outward-facing: In upper quartile for suppliers, and in the upper quartile for customers.

The strategies offered demonstrated upward or downward integration as well as the degree of integration. This research revealed that companies with wider integration with suppliers and customers have a greater degree of performance improvement in comparison with the ones having narrow or biased integration.

Frohlich and Westbrook [14] have also proposed four strategies for supply chain integration, as follows.

Model A: Web-based Low Integration

Model B: Web-based Supply Integration

Model C: Web-based Demand Integration

Model D: Web-based Demand Chain Management Integration

The first strategy integrates only internal processes by automating each internal fucntios resulting in little to no integration among suppliers and customers. The second strategy involves information sharing and strategic connection with suppliers whereas the third strategy involves integration among the company and its customers. This is mainly about the inverse flow of information from customers to suppliers. A fully integrated firm would have information flow in both directions.

Bagchi and Skjøtt Classification

Bagchi and Skjøtt [10] defined supply chain integration mainly the categories information and organizaional integration. They inspected the significance of information and organizational integration within a supply chain network. They intoduced three levels of supply chain integration: Low, Medium and High.

They describe a company's level of integration based on different levels of the use of four information integration categories: 1)Transaction systems; 2) Communication Systems 3) track and- trace systems; and 4) Relationship Management. For instance, a company that is still utilizing legacy systems which include MRP II systems and provide communication with the supply chain partners with fax or phone along with a limited use of e-mail/Internet, is classified to possess a low integration. Whereas, a company that utilizes ERP and supply chain planning software and gets a considerable use of bar codes, EDI and XML technology for data transfer and communication as well as providing its online partener relationship in production and sales plans, is classified to possess a high integration.

To enhance integration, they classified organizational integration into eight categories: 1) Orientation; 2) SCM Logistics in the organization; 3) Level of integration; 4) Communication across the supply chain; 5) Governance Structure; 6) Governance Structure; 7) Formal lateral organizations and 8) Performance measurement. For instance, a firm using a logistics integration and/or SCM function at the top tier of the organizational hierarchy with supply chain members, inter-organizational and inter-functional teams, is categorized to possess a high integration. Such highly integrated firms usually make use of process oriented organization structure and have joint planning and measure supply chain performance and customer satisfaction.

They have introduced the characteristics namely, low, medium, and high integration in supply chains based on seven categories including: 1) Communication across the SC; 2) Shared decision making; 3) Risk, cost, and gain sharing; 4) Sharing ideas and institutional culture; 5) Skills sharing; 6) Investments; and 7) Formal lateral organizations. Often now communication systems are insufficiently connected and the flow of data goes through a path which has very little direct communication in a low integration supply chain. However if there is a high level of integration, then there would mostly be much more direct connections to the customers at different commitment levels over the attached companies in a supply chain. The members from the customers can then directly communicate with the supplier members. The personnel of both supplier and customer companies ail then be in close contact with each other.

2.3. The Proposed level of organizational integration Framework

This proposed framework classifies the level of organizational integration in four categories:

- No Integration
- Low Integration
- Medium Integration
- High Integration

This classification is based on a progressive integration of a number of stages to develop a supply chain. According to some researches [8, 13, 22], the stages of integration are internal integration, supplier integration and customer integration respectively. Creation of integration in this order would result in a high integration.

To start with, we range the scores from 0 to 100, where 0 means not integrated and 100 stands for fully integrated. Then we define four exclusive groups, each representing the integration strategies of the firms and classifying these into appropriate groups. According to this proposed framework, the first category is classified as “No Integration”. In this category the scores for suppliers and customers integration are below 25. At this level, the score of internal integration is insignificant and irrelevant. The overview of the lowest level of integration in all the frameworks mentioned in this study provides a proof for this classification, as it contains no integration with suppliers or customers. In this framework, we rely more on suppliers’ and customers’ integration because based on some researches [8, 9, 21], integration between supply chain members occurs when manufacturer, supplier and customer integrate together.

The second category, based on three significant conditions, is classified as “Low Integration”. These three conditions include a score of 25 or higher for internal integration, a score of 25 or higher for suppliers’ and customers’ integration, as well as, a score below 50 for customers’ integration response. At this level, the firm has started creating integration within supply chain members, however, it is in the lowest stage of integration as either supplier or customer integration is between 25 and 50 score.

The third category is categorized as “Medium Integration”. At this level, internal integration has a score of 50 or higher and suppliers’ and customers’ integration have scores of 50 or higher, but suppliers or customers integration has a score below 75. At this stage, the firm is in medium stage of integration with supply chain members because one of supplier or customer integration is between 50 and 75 score.

Finally, the last group is classified as “High Integration”. At this level, suppliers, customers and internal integration have scores of 75 or more.

There are some significant differences between our proposed framework with the two existing framework namely, Bagchi and Skjøtt framework and Frohlich and Westbrook framework. Firstly, Bagchi and Skjøtt [22] did not classify “No Integration”, which refers to existing traditional firms with no internal or external integration [11, 23, 24]. Secondly, in Bagchi and Skjøtt survey, internal and external dimensions of supply chain integration are not categorized. They consider the whole supply chain integration. Finally, in Frohlich and Westbrook [17] framework questionnaire, only the arcs of integration based on external integration view (supplier integration, customer integration) are investigated, and internal integration is not considered.

3. CONCLUSION

In highly competitive environments, companies are forced to implement supply chain management (SCM) in order to reach competitive advantages and enhance their supply chain performance. SCM consists of integration, co-ordination and collaboration within organizations and all over the supply chain. That means, that the supply chain management requires internal (intraorganisational) and external (interorganisational) integration [9].

Supply chain integration, if applied effectively, is known to bring about a significant improvement to all companies. The target of seamless supply chain is to enhance material and information flows within a company and also connect it with other supply chain members. With the technology available today, very intimate, beneficial and profitable supply chain integrations can be structured.

One important visage of integration is the level of integration which can be identified by the number of activities through one dimension. In today’s global competition, companies strongly need to adopt advanced practices to achieve a high integration within their supply chain. Many researches have been conducted which approve a much higher operational and business performance of firms while the degree of integration rises [8, 9].

Knowing the level of supply chain integration is a key factor for each company to improve their integration. A framework that measures the level of integration is essential for each firm in order to compete in today’s global economy. This proposed framework derived from some important frameworks, gives the essential and advanced tool needed to measure the level of integration in the manufacturing sector. It will be evaluated and validated for the manufacturing sector in the next paper.

Our study introduced the level of organizational integration framework that measures the level of integration of a firm using the relationship among the dimensions of supply chain integration in the manufacturing sector. In the research model introduced in the literature review in the scope of supply chain management, we demonstrated that internal integration has resulted on both supplier integration and customer integration.

Our study presented theoretical and literature review evidences for proposed level of integration framework. We have also shown that internal and external integration have impacts on level of integration between firms resulting in improvements of competitive capabilities in firms. Based on this study, a firm's integration capability may be enhanced, if more attention is given to supplier and customer integration.

Our study's limitations relate to its scope and method. Our model is structured for the manufacturing sector, not the business sector. Further studies should include a framework applicable to different enterprises.

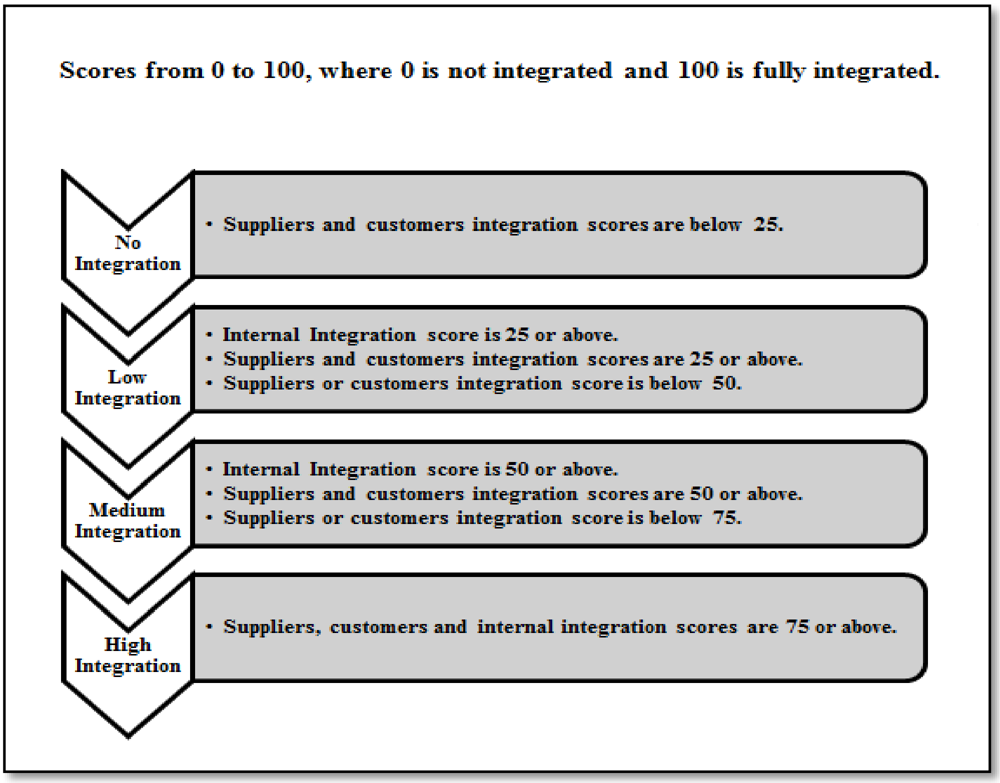


Figure 1: Operationalization of level of integration.

REFERENCES

[1] Nunes, M.B., Annansingh, F., Eaglestone, B., and Wakefield, R. 2006, Knowledge management issues in knowledge-intensive SMEs. *Journal of Documentation* 62:101-119.

[2] Boehme, T. 2009, Supply Chain Integration: A Case-based Investigation of Status, Barriers, and Paths to Enhancement. The University of Waikato.

[3] Kotler, P., and Keller, K. 2009, *Marketing Management*. London: Pearson Prentice Hall.

[4] Kim, S.W. 2006, The effect of supply chain integration on the alignment between corporate competitive capability and supply chain operational capability. *International Journal of Operations & Production Management* 26:1084-1107.

[5] Stadtler, H. 2008, *Supply chain management and advanced planning: concepts, models, software, and case studies*: Springer Verlag.

[6] Christopher, M. 2011, *Logistics and supply chain management* Harlow, England ; New York: Financial Times Prentice Hall.

[7] Zhao, X., Huo, B., Selen, W., and Yeung, J.H.Y. 2011, The impact of internal integration and relationship commitment on external integration. *Journal of Operations Management* 29:17-32.

[8] Frohlich, M.T., and Westbrook, R. 2001, Arcs of integration: an international study of supply chain strategies. *Journal of Operations Management* 19:185-200.

[9] Gimenez, C., and Ventura, E. 2005, Logistics-production, logistics-marketing and external integration: Their impact on performance. *International Journal of Operations & Production Management* 25:20-38.

[10] Bagchi, P., and Skjott-Larsen, T. 2002, Challenges of Integration in Supply Chain Networks: An European Case Study. .

[11] Stevens, G.C. 1989, Integrating the supply chain. *International Journal of Physical Distribution & Logistics Management* 19:3-8.

[12] Stewart, G. 1997, Supply-chain operations reference model (SCOR): the first cross-industry framework for integrated supply-chain management. *Logistics Information Management* 10:62-67.

[13] Metz, P.J. 1998, Demystifying supply chain management. *SUPPLY CHAIN MANAGEMENT REVIEW* 1:46-55.

[14] Frohlich, M.T., and Westbrook, R. 2002, Demand chain management in manufacturing and services: web-based integration, drivers and performance. *Journal of Operations Management* 20:729-745.

[15] Lambert, D.M., Cooper, M.C., and Pagh, J.D. 1998, Supply chain management: implementation issues and research opportunities. *International Journal of Logistics Management, The* 9:1-20.

[16] Wong, C.Y., and Boon-itt, S. 2008, The influence of institutional norms and environmental uncertainty on supply chain integration in the Thai automotive industry. *International Journal of Production Economics* 115:400-410.

[17] Fiala, P. 2005, Information sharing in supply chains. *Omega* 33:419-423.

[18] Lotfi, Z., Sahran, S., and Mukhtar, M. 2013, A Product Quality - Supply Chain Integration Framework *Jounal of Applied Sciences* 13:36-48.

[19] Narasimhan, R. 1997, Strategic supply management: a total quality management imperative. *Advances in the management of organizational quality* 2:39-86.

[20] Oghazi, P. 2009, Supply Chain Management – An Empirical study of Swedish Manufacturing Firms' Enterprise Systems Adoption, Supply Chain Integration, Competition Capability and Performance. In *Department of Business Administration and Social Sciences, Division of Industrial Marketing, e-Commerce & Logistics*. Universitetstryckeriet, Luleå: Luleå University of Technology.

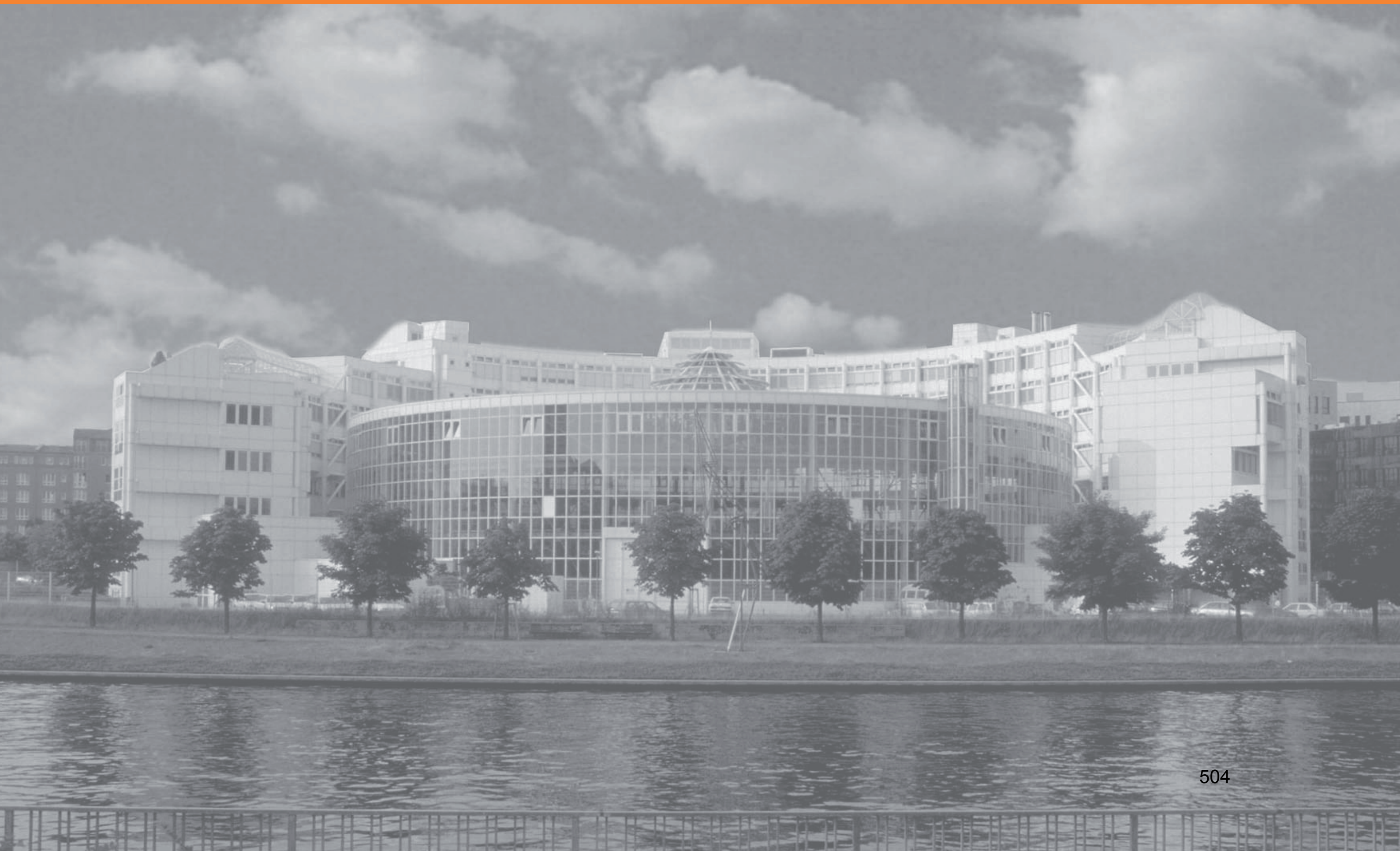
[21] Flynn, B.B., Huo, B., and Zhao, X. 2010, The impact of supply chain integration on performance: A contingency and configuration approach. *Journal of Operations Management* 28:58-71.

[22] Bagchi, P.K., and Skjøtt-Larsen, T. 2004, Supply Chain Integration in Nordic Firms. In *2nd World Conference on POM*. Cancun, Mexico. 1-23.

[23] Zubova, K., and Arikainen, O. 2012, Procurement Process Integration (PPI) in Swedish and Ukrainian Companies Producing Machinery and Equipment: Comparison in terms of the level of integration, the tools of integration and the barriers to integration from buyers' perspective. LNU.

[24] Narasimhan, R., and Kim, S.W. 2001, Information system utilization strategy for supply chain integration. *Journal of Business Logistics* 22:51-75.

Session 15
Energy Assessment



GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

15.1 Visual analysis of performance indicators and processes in modern manufacturing

S. Hesse [1], V. Vasyutynskyy [1], D. Nadoveza [2], D. Kiritsis [2]
[1] SAP AG, Germany
[2] École Polytechnique Fédérale de Lausanne EPFL, Switzerland

Abstract
The amount of business information in different levels and areas of manufacturing grows constantly, so does also the need for quick analysis of it. Despite of existing methods of data analytics, at the end the humans have to analyze the results and make decisions. This may overstrain the users, which have to access heterogeneous data sources and evaluate a plenty of data views in different dashboards and reports to get all the information they need together. The project PLANTCockpit explores the new ways of integration of information from diverse levels of manufacturing as well as for comprehensible visualization of it. This will improve the decision making process and help make the manufacturing more effective and sustainable. The paper demonstrates the developed approach on two use case studies of analyzing the performance indicators and processes, showing the two perspectives of the analysis. The paper also concerns the simplifying of the configuration processes for the end user.

Keywords:
Key performance indicators; process analysis; configuration; visual analysis

1 INTRODUCTION

In the modern manufacturing, it is important to identify the problems quickly and make the proper decisions. Except of the evident economic and competitive advantages of doing this (e.g. quicker time to produce, less errors), the quick and correct operational decisions are also highly important for sustainability and environmental performance. For example, by analyzing the energy consumption of a company, the saving potential can be identified. Another example is quick detection of the material delivery problems that is quite important in foods and beverage industry where the raw materials and semi-products may deteriorate very quickly. Thus if one raw material can be replaced by another one then the production manager should quickly identify the possible consequences (e.g. deterioration of other raw materials) and take appropriate actions (e.g. reschedule the production). With the visualization of environmental performances and relating them with different production factors (indicators), producers are able to optimize their production and products to be more sustainable and environmentally friendly and at the same time be economically more reasonable.

The idea of the European research project PLANTCockpit [1] is to develop the framework that integrates the data from the different levels of the automation pyramid, and to visualize them in an integrated cockpit, cp. Figure 1.

Furthermore, this cockpit should not simply provide various information from the different production levels and systems, but it has to provide a framework which could be used to link (aggregate) this information in order to infer new knowledge(information) and increase awareness of the cockpit's user.

Thereby two perspectives of the decision making and responsibilities have to be supported. The horizontal perspective provides the support within one level or process (e.g. on Manufacturing Execution level within one production line for a production line manager) and is prior to operative decisions.

If the necessary data are not available within one level, the responsible person should get and analyze data from other levels. For example, he should get data from higher level ERP (Enterprise Resources Planning) level to assess the details on the problematic raw material deliveries. In this case the vertical perspective of data analysis takes place.

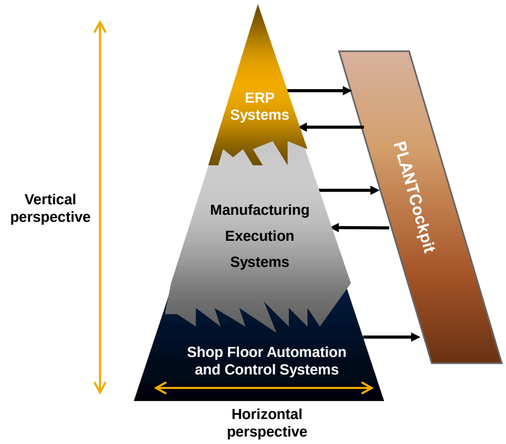


Figure 1: Automation pyramid and place of PLANTCockpit.

Another example of the vertical perspective is the analysis of the overall status of production by factory managers, which should assess aggregated information of the factory and the factors influencing this state. An example of such state is the usage of recycled raw material. For this purpose, the data from different levels of the automation pyramid should be

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

aggregated and the dependencies between data should be presented.

The paper demonstrates the necessity of the combination of these two perspectives in one cockpit, shows the example of business logic that should be provided in both horizontal (Section 2) and vertical perspective (Section 3). A specific attention is paid the configuration of the cockpits specific for a use case or responsible person, which is a quite complicated task due to the fact that several systems are involved and the addressed business processes are complex.

2 BUSINESS LOGIC FOR PROCESS ANALYSIS AND ITS CONFIGURATION

2.1 Process analysis for material deliveries

A typical scenario of the process industry has from 50 to 100 process/production orders per plant and day with an average of about 15 material items per process order. The employees within the production planning department have to go through several monitors and data sources to ensure that the final products are being produced at the right time with the right quality and quantity, at the same time consuming the minimal quantity of water and energy. This requires today an active search in different data sources and linking disparate data; a process which is very time consuming and mostly done when delays have already occurred and thus it is already too late to find a solution. These deviations rise up when raw materials or semi-final products are not provided at the right time at the production line. The reasons for this may be: problems/delays in fulfilling the production orders, problems in the logistical chain, delays on transports from external suppliers, productions in time but with insufficient quality, etc. The information concerning the delays in the procurement and transport of these raw materials and semi-final products today is not automatically redirected to the production planner and as a result, valuable time and resources are lost in order to find alternative raw materials and/or reschedule process /production orders.

The chosen use case is that of a manufacturer of nonalcoholic beverages. This use case consists of different activities necessary to complete order-to-delivery process and provide the ordered goods to customer right on time and with required quality (e.g. organic products).

The manufacturing plant first receives purchase orders from customers. The processing step is the actual production of the drinks. Then a quality control is made before filling the goods into containers. The containers are then transported inside the plant to the storage where they await external transport to their final destination for delivery.

Each of these steps is described by business objects in the form of orders (e.g. process order, filling order, etc.). These orders contain such vital information such as start and end times, resources to be used for task completion, etc. The problems arise when the manufacturer receives up to a 100 customer orders a day. Indeed for each customer order the other orders from processing to delivery have to be created by the employees of the production planning department. It is inevitable in any manufacturing business that deviations will arise, resulting in the need for active searches for a solution.

In the current situation of the manufacturer, the production planners have to sort through manually the various orders, a process that is highly time-consuming, resulting in solutions that are usually discovered too late. Thus the objective is to develop the configurable manufacturing dashboard which will be able to visualize the deviations in the production and to supply the appropriate user only with relevant information automatically when production deviation arises. This concept will gather all this information and provide a relevant information to the appropriate user that will help in the decision making process. The decision making will be not only a matter of the experts that have to access different systems to get the information they need, but be a much more automated process where the routine work of getting the necessary data becomes transparent to the user and where the user get all the information he needs in a visually comprehensive form.

2.2 Overall Architecture

PLANTCockpit solution is based on the information which is imported from the various external sources. In order to provide data, a message oriented middleware accesses heterogeneous data sources using dedicated adapters and converts the received data into on unified data format. The architecture of the solution is described in detail in [1].

The implementation for this paper accesses the SAP ERP as external system which provides the necessary data in form of business objects such as purchase orders, process orders and material reservations. This data has to be processed, filtered and visualized by the PLANTCockpit solution as an important part of the overall business process.

The data access to the external system is done via a special ERP Adapter Function Block which is the component type responsible for the interaction with the external systems. The Adapter Function Block type component type is described in [1]. The data from the external system are transferred over the Adapter function block to the Delay Resolver Function Block, which is the main component responsible for execution of the business logic specific for this prototype.

The data prepared by the Delay Resolver Function Block is consumed by Visualization Engine Layer which further prepares a visual representation of the data and delivers it to the end user.

Finally the prepared data is displayed to the end user in a browser-based HTML5 frontend which is located in the Presentation Engine Layer.

2.3 Visual representation of production processes and details

Since the responsible persons have to make their decisions very quickly, the visual representation of the production problems and details like alerts plays an important role. For the scenario of tracking material delays a Time Line oriented visualization is chosen to couple the process orders with the given scheduled start and end times. Every line contains one header on the left side, labeled with the name of the production line. This fixed header area is accompanied by a following dynamic area visualizing single processes and further required information. In order to provide an overview of the entire production environment, the single production lines are combined in an overall view and the visualization of the processes is synchronized to a timeline. This style is visualized in Figure 2.

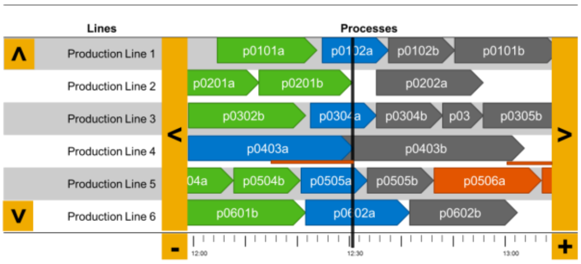


Figure 2: Time-line process visualization.

Through the line based visualization every line displays processes which belong to a specific production line. Every process is represented by a geometric form which reflects an arrow shape. The process shape is labeled with the ID of the shape and coloured symbolizing the state. It is possible to define different process statuses such as: finished process (green), on-going process (blue), scheduled process with no errors (grey), process with error (red) and process with warnings (yellow). A current time indicator is displayed as a solid black line in order to provide the user with the possibility to evaluate the processes in the current time window.

An additional important functionality is providing further information to the user. By clicking or tabbing on a process, a popup appears displaying additional information, gathered from the ERP system. This may include planned start and end times, actual timings, system status and ERP messages. Other related processes can also be visualized in drill-down views. In the same screen, the user can access a quick link to corresponding user interface within the SAP ERP system to trigger further appropriate actions.

2.4 Business Logic behind the prototype

The Delay Resolver Function Block is taking care about the execution of core part of the business logic. The overall business logic is illustrated in Figure 3 and briefly described in the following text.

The whole business logic is triggered by an incoming delivery delay notification from external system. The source of the delay might be insufficient production capacity's, slower transportation or waiting periods. The data embodied in this message is utilized to get insights about the material purchase order that is delayed. Then the Delay Resolver Function Block requests the detailed information about the purchase order from the Adapter Function Block which accesses the ERP.

This information is then processed to elaborate which materials were ordered. One or multiple material numbers might be assigned to one purchase order. For each of the material, I a request to Adapter Function Block is created to check whether reservations exisits for the given material.

The result contains one or multiple reservation numbers for each of the material that has been sent along with the message. After processing all of the results a list of reservation numbers are available to the Delay Resolver Function Block that has to be used to query for details of the reservations by sending multiple messages to the Adapter Function Block.

Process order numbers which have been registered to use materials are enlisted as part of the result messages. Processing all the responded result messages will provide a complete set of affected process orders.

For those orders a status has to be calculated and will be cached. Due to the fact that the affected process order is most problably just a subset of the relevant scheduled ones needed for the visualization an additional message has to be sent to the Adapter Function Block to gather all the scheduled and relevant orders for a given time frame.

Information provided by the process orders are enriched with the calculated status for the affected ones. All the other process orders stay untouched if there are no dependencies with the affected otherwise their status is recalculated as well. Finally a delay notifcation response message is generated indicating if the processing phase was executed correctly and in parallel the data is prepared for consumtion from the visualization.

The visualization is taking care about the update of the visual representation to display the correct and most up to date information to the end user.

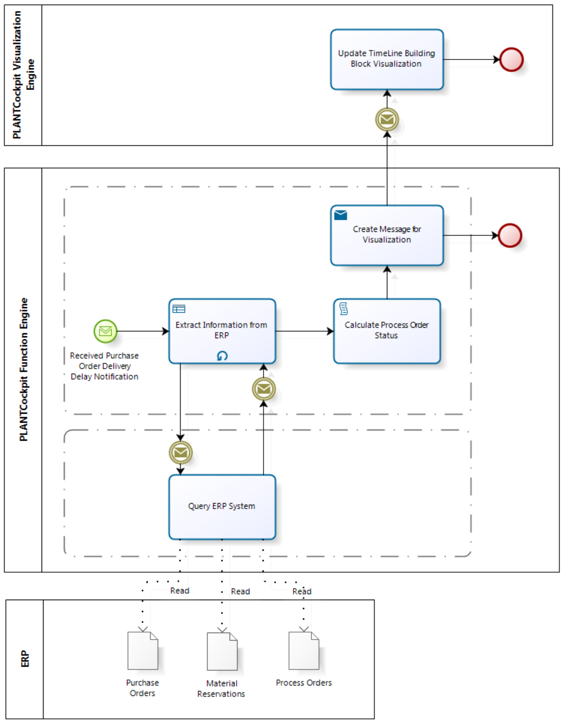


Figure 3: Overall Business Process Model (simplified).

2.5 Realization of business logic using rules

Quite often, for developers, it is hard to change the business logic and for domain experts, it is impossible to verify the business logic and even harder to change it [3].

In case when we want to change the behavior of the application, we'll have to recompile and redeploy the whole application. Furthermore, it is not only difficult to represent business logic in a programming language, but also hard to differentiate between code that represents the business logic and the infrastructure code that supports it [3].

Therefore we are proposing the rule-based business logic representation. In this approach we declare rules in pretty much the same way as the business analyst does the requirements – as a group of *what-if* statements. The rule engine can then take these rules and execute them over our data in the most efficient way. This is different from traditional programming languages where the developer has to specify how it needs to be done.

In PLANTCockpit we decided to use Drools rule engine (JBoss Community [4]). Drools is a Business Logic integration Platform (BLiP) written in Java and licensed under the Apache License, Version 2.0 (The Apache Software Foundation [5]).

As previously stated, the whole process starts with the arrival of a delivery delay notification. Triggered by it, the function block sends various messages to the Adapter Function Block to extract the details of the purchase order, materials reservations as well as process orders.

Afterwards the statuses of the process orders get calculated. This calculation is realized using the special rules for status calculations. These rules are specified by the system administrator and/or business analyst and they are applied to the all processes which are considered by the PLANTCockpit.

For the data preparation and filtering, rules are again employed. Basically, these rules specify which processes have to be visualized. It could be said that these rules cover only the parts of business logic which is specific for the certain end user or user type. They are specified by the system administrator or even by the end user directly.

Finally, the visualization engine then processes the data and displays the data in an appropriate form to the appropriate end user.

The following example (Figure 4) illustrates the application of rules for filtering the information for the end user. However this rule is far from complete and could be seen just as a mockup. In a real scenario rules could be very complex, therefore, for this work it is crucial to explore the opportunities for easy rule generation and configuration.

```
rule "ProductionManager User rule example"

when
   $response : MessageHolder
   $pod : ProcessOrderDetails
   $relevantPods : ProcessOrderDetails( ) from
collect( ProcessOrderDetail( status matches
"PROCESS_DELAYED") from $pod )

then
   $response = new MessageHolder($relevantPods)

end
```

Figure 4: Example of a Drools rule.

In this simple rule, it is basically stated that the production manager will receive information only about those process orders which are delayed.

By analyzing the whole business logic and the rule based approach we can say that we distinguish two basic types of rules in our solution:

<u>Common Business rules</u>

Common Business rules represent the business logic, which should be executed no matter who is accessing the system. These rules could be executed periodically or triggered by events.

In PLANTCockpit, the typical example for common business rules is the calculation of the process order status. For each process type it is possible to define the status calculation rule. Applying the rule based approach in this case allows very flexible business logic and interpretation of the different factors which influence each process order.

In case when one process order changes its status it is possible to define the overall rule which will update the status of all the other orders which are affected by the change of status of the initial order. This means that with the overall rule we can specify the dependencies between the various processes. This concept allows the so called impact assessment where the system can foresee the future deviation which is the consequence of the current deviation and it is not explicitly modeled in the system. With these rules, we can say that the implicit expert knowledge is captured in the system and made explicit and available to the different actors.

<u>User/Role specific business rules</u>

User/Role rules represents the business logic which is specific for the end user or role in the organization. These rules specify the application's behavior which is required by the specific user or user type. Typically these rules are defined by the system administrator or directly by the end user.

In this case user business rule is defined for the information filtering. The idea is to provide only the relevant information to the end user. The relevancy is defined by the rule which takes into account different factors which determines the information relevancy in the certain situation. For example, one user is interested only in the process orders for the certain product type and/or production line, and/or processes with a certain status.

This concept increases the user awareness and reduces the information overload by serving only the important and relevant information to the user. Furthermore, information filtering done in the server side facilitates the development of the thin client and high flexibility of the user interface.

This rule-based realization of the business logic offers the following key advantages:

- Understandability – Rules are easier to understand than the code written in traditional programming language.
- Maintainability – Since rules are easier to understand, it directly leads to the fact that it is easier to maintain it.
- Extensibility – With the rule-based business logic realization it is possible to add new business logic without big customization efforts. It is easier to add a new rule then to change the program code and recompile and redeploy the application.
- Requirements – Some business requirements could be directly translated into the rules.

3 PERFORMANCE INDICATOR ANALYSIS AND ITS CONFIGURATION

The interaction patterns for the person responsible for higher-level management tasks (e.g. production line manager) are different from the common interaction tasks for the production planners as described in section 2.1. While the production planners look into future, the higher level management is more oriented to analysis of aggregated information with a focus on supervision. A responsible person within the production planning system has to plan according to internal and external events such as production information from other locations, delivery or internal events such as lack of raw material in the interim stock, which may affect the area of the responsible person. An active search for such events may consume too much time and the use of multiple process monitors to search for production issues may not being efficient. For that reason, a single monitor displaying few aggregated KPIs in one dashboard has been developed in [1] and [2].

3.1 Approach for visual performance indicator analysis

The challenge for these common KPI dashboards, in contrast to the process and event monitor, is the visualization and analysis of links and relationships between KPIs, which aggregates the various levels of the business (production, supply chain, assets etc.) for task of aggregated information oriented supervision. If the responsible is aware of these relationships and is able to understand the cause of an event, it would lead to more effective decision making in case of e.g. delays, machine problems, stock shortages as well as high energy or water consumption. Furthermore, by visualizing the relationships between the different aspects of the business, which before were hidden in the heads of the domain experts, a decision maker is able to understand the interdependencies and causalities of the different actions and situations happening on the different business levels and to link them with the overall environmental performance of the enterprise.

KPIs have different scope and the intrinsic connections between them may have different nature. The scope of each KPI may refer to different levels and entities, like a product, a production line, a production site or within the entire company. Furthermore the KPI can include the information expressing a state update from a supplier or an internal state of a dedicated machine. Thus, for assessing the whole picture of the production, not only the KPIs, but also the dependencies between them have to be analyzed.

To support the user in this task, [2] proposed to present the KPIs in a KPI dependency graph, presenting the KPIs and links between them. The further development of this approach in this paper is to divide the dependency graphs into abstract (model level) and specific (instance level) KPI dependency graphs.

While the abstract KPI dependency graph is a single graph template which is modeled to be valid for the entire enterprise, we introduce specific KPIs dependency graphs, which are instantiated based on the modeled structure and templates. Such instantiated KPIs are combined into views, which may contain only some few KPIs representing a dedicated perspective, linked to the data sources and including the current or historical values. One perspective may include specific environmental KPIs; while another perspective can consist of production line specific KPIs.

The concept of abstract and specific KPIs dependency graphs is based on the performance indicator reference model [6] and allows a cascading definition of KPIs and relationships between them. It extends common KPI standards such as ISO 22400 [8] by refining every KPI for each level in the automation pyramid and links them together. In our case, refinement means among others the definition of one abstract KPI to a more specific instance KPI. For example, the GHG (Greenhouse gases) KPI for one enterprise can be cascaded to several production sites and then to different production areas. Using the abstract models and specific views, the common terminology and approach for analysis of KPIs are supported, and on the other hand the dependency graphs are adjusted to the specific production level, department or person. The abstract graphs are created by the dedicated experts responsible for several areas, whereas the specific graphs are created by experts responsible for one specific area and are derived from the abstract graphs.

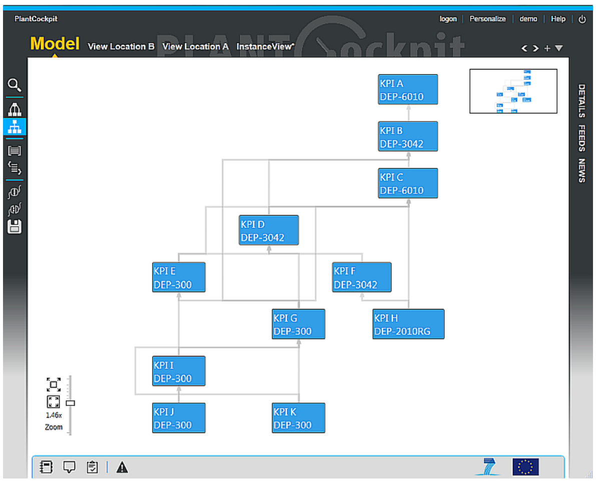


Figure 5: Example of Abstract KPI dependency graph.

Figure 5 depicts an example of abstract model, where KPI templates and relationships between them are represented. Based on the definitions from [6], we support following information items, which are valid on model level:

- Name of the KPI and General description,
- A set of units used for KPI (e.g. %, number of pieces etc.),
- A business unit or business area responsible, and a responsible technical person,
- An association to related business processes,
- A set of general tags,
- Multiple links to other KPI models.

The template approach of abstract dependencies within the prototype supports multiple dependencies between KPIs. Sources for the model might be common KPI systems such as Balanced Scorecard [7] or KPIs e.g. for Environmental Issues [9] as well as mathematical or collaborative approaches.

3.2 Specific KPI view configuration

The creation of a new specific view starts with the selection of a single node, which corresponds to a KPI template. If the user has dragged the node, the prototype looks into the model and gathers the dependencies to nodes which are direct or indirect parents of the selected node. These parental nodes will be added to the view as minimized, symbolic nodes.

Furthermore the links between the selected node and the parental nodes will be painted to the canvas. This behavior was chosen to preserve and to visualize the hierarchy of the selected node. After selecting a node, the user can update the KPI template provided by the abstract model and can connect the selected node to the data source. Additional information which may not be provided by the template could be the dedicated responsible person for this KPI, personal targets or thresholds, personal comments or tags.

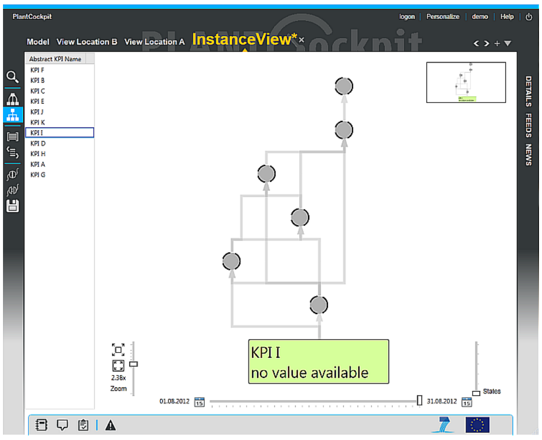


Figure 6: Creation of a new instance view.

Figure 6 presents the creation of a new view. In this example, KPI I was dragged from the list of available KPI types (on the left) to the canvas. Then the prototype creates the hierarchy by using the model. In this case, several nodes are direct or indirect parent nodes to KPI I. This means that changes in the value of KPI I may influence the parent nodes. If the user wants to assess the KPIs corresponding to parent nodes, he can activate them, if his user rights allow to get the data from these nodes. Then the nodes will be transformed from grey circles to KPI nodes and can be used during analysis.

The presented approach of abstract and specific views for KPI dependency models allows the easy creation of views specific for a dedicated use case, which is very relevant in the modern production systems where the situation (like environmental awareness, customer orders, material and production flows, areas of responsibility, machine states etc.) may change very quickly. To keep pace with these changes, the KPI analysis views should also change very quickly which is supported by our approach. On the other hand, the uniform definition and understanding of KPIs through different areas and levels of production is ensured by the abstract KPI dependency graphs. As result, the dependencies between KPIs can be analyzed in an efficient way, which is useful in such scenarios as root-cause analysis, fault-impact, quick fault detection, visual analysis, training of new colleagues, documentation of issues etc.

4 CONCLUSION

Achieving sustainability is a complex process which covers various processes, not only within the enterprise but also from the entire ecosystem. In case of enterprises (producers) from the operational aspect it involves the analysis of the various production processes, logistics, economical aspect and environmental indicators, which is the basis for taking appropriate actions. Before, combining all these factors and summarizing hem in one solution was pretty hard to imagine. Now, with our proposal of using the graph-based approach for the creation of dedicated perspectives allows the supervision of environmental KPIs along with their direct causes in the production on one screen. Furthermore, our approach is not limited only to mathematical dependencies, since social and logical influences can be also modelled and integrated into the overall economic model of the enterprise. Moreover, the experts may directly compare the environmental (like “Particle Emission to Air per Output” KPI) and other production related KPIs (like “Direct Run Through” KPI) to find the appropriate balance. Also by linking the completely dispersed information, the new knowledge is gained and overall environmental awareness of the product and production processes is achieved.

The paper has demonstrated the necessity of considering both horizontal (operational) and vertical (strategical) perspectives during analysis of business processes and performance indicators in production as well as for consideration of the environmental impact of the production. Both perspectives have been addressed in the corresponding prototypes. In particular the topic of easier configuration of views has been considered, which is crucial for a quick adjusting to the new or changing business process. As result of the combination of visual approach with business information in form of rules and dependencies, the users get more full and up-to-date awareness about different production processes and dependencies between them.

Future work will concentrate on the further automation of the configuration process. Also further convenience features for the users will be supported, including presenting multiple dimensions in one data source.

5 ACKNOWLEDGMENTS

The authors would like to thank the European Commission for co-funding of the research project PLANTCockpit under the project number 260018.

6 REFERENCES

[1] Vasyutynskyy V., Hengstler C., Nadoveza D., McCarthy J., Brennan K. G, Dennert A., 2012, Layered Architecture for Production and Logistics Cockpits. Proceedings of ETFA 2012, Krakow, Poland.

[2] Hesse S., Vasyutynskyy V., Hengstler C., Rosjat M., 2012, Modeling and Presentation of Interdependencies between Key Performance Indicators for Visual Analysis Support, Proceedings of the Conference APMS 2012, Rhodes Islands, Greece.

[3] Bali, M., 2009. Drools JBoss Rules 5.0: Developer's Guide. 2009: Packt Publishing Ltd.

[4] JBoss Community. Drools - The Business Logic integration Platform. Retrieved 2013, from http://www.jboss.org/drools

[5] The Apache Software Foundation. Apache Licence, Version 2.0. Retrieved 2013, from http://www.apache.org/licenses/LICENSE-2.0.html

[6] Hesse S., Wolf B., Rosjat M., Nadoveza D., Pintzos G. 2012. Reference model concept for structuring and representing performance indicators in manufacturing, Proceedings of APMS 2012, Rhodes Islands, Greece.

[7] Cobbold, I. and Lawrie, G. 2002. "The Development of the Balanced Scorecard as a Strategic Management Tool". Performance Measurement Association 2002.

[8] ISO/DIS 22400-1. Manufacturing operations management - Key performance indicators -- Part 1: Overview, concepts and terminology.

[9] DVFA, 2009, KPIs for ESG: A Guideline for the Integration of ESG into Financial Analysis and Corporate Valuation, EFFAS, the European Federation of Financial Analysts Societies

GCSM 11th Global Conference on Sustainable Manufacturing

2013
23rd - 25th September
Berlin - Germany

15.2 Lean and green framework for energy efficiency improvements in manufacturing

N. Weinert[1], J. Fischer[1,2], G. Posselt[2], C. Herrrmann[2]

[1] Corporate Technology, Siemens AG, 81739 Munich, Germany

[2] Technische Universität Braunschweig, Institute of Machine Tools and Production Technology, Research Group Sustainable Production and Lifecycle Engineering, 38106 Braunschweig, Germany

Abstract

With energy efficiency being one of the major development lines in production planning and control today, recent R&D activities have created a large amount of possible measures for improvements. However, in the daily business situation of existing factories, the implementation of available measures often still is limited to most obvious improvements, commonly known as “low hanging fruits”. Further implementations are often neglected due to time, cost or information restrictions. For overcoming this shortage, the Lean and Green Framework introduced in this paper has been developed, providing a standard process of identifying and implementing energy efficiency improvements. The framework provides structured processes for the acquisition of production as well as energetic information on the considered factory, for deriving specific areas where, according to this information, improvements are needed and for the identification of appropriate measures to achieve the identified improvements.

Keywords:

Energy efficient production, sustainable Production, lean Production

1 INTRODUCTION

In recent years, energy efficiency has become more and more important for companies in the manufacturing industry. While the so called “low hanging fruits” are quite easy to find, they are limited in terms of their improvement potential, demanding more sophisticated measures to further foster energy efficiency. Hence, numerous publications, initiatives and research projects introducing new methodologies and guidelines with the aforementioned goal have been presented in recent years (e.g. [1-2]). Improvement measures can be found on all levels (from factory to process level) and within all disciplines (e.g. process and process chain design (e.g. [3]), production planning (e.g. [4-6]), or machine design (e.g. [7])). Hence, for fostering all improvement potentials the factory has to be considered from a holistic perspective, including production, technical building services (TBS) and the building shell, as defined by [8]. Taking also into account the conventional measures for optimizing production systems from e.g. the Toyota Production System (e.g. [9-10]), industrial engineers and managers are facing the challenge of finding and selecting appropriate measures for their respective factory or production system, by estimating the effects of different measures for several criteria. A structured process is required that supports the identification of improvement potentials and adequate measures to achieve the identified benefits. In this paper the Lean and Green framework is introduced as an approach to simplify it for production managers and industrial engineers as well as for system designers and maintenance staff to cope with these challenges. Investigating the correlations between lean and green paradigms within discrete part manufacturing is still a relatively new field of research and hence only few publications have been made so far (e.g. [11-13]).

2 LEAN AND GREEN FRAMEWORK

2.1 Overview

Basically, the developed Lean and Green Framework aims on supporting the process of evolving an existing lean-optimized factory into one optimized for both, lean and green objectives by iteratively applying adequate measures. The effort for applying a specific measure may differ significantly, e.g. replacing a large drive by one with a higher efficiency can be much more cost intensive than changing behavioral patterns of employees, while the latter requires a much higher effort in planning and implementation than the former one. It is evident that implementing measures is not trivial in every case, but can require a remarkable effort for planning and realization. Especially if the person responsible is not an expert on energy efficiency, extensive research for adequate measures is not a suitable option in a daily business environment. For overcoming this shortage, the lean and green framework is designed as a process consisting of the steps for acquiring information on the given situation, identifying need for actions based on the acquired information, and selecting and implementing appropriate measures for improving the initial situation. The whole framework is designed as a process based on continuous iterations, thus allowing consecutive measures to be applied. Additionally, by repeatedly checking improvement potentials, new developed measures for improving the energetic efficiency of a factory or a part of its production are successively integrated into the framework. An overview of the framework is depicted in Figure 1.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

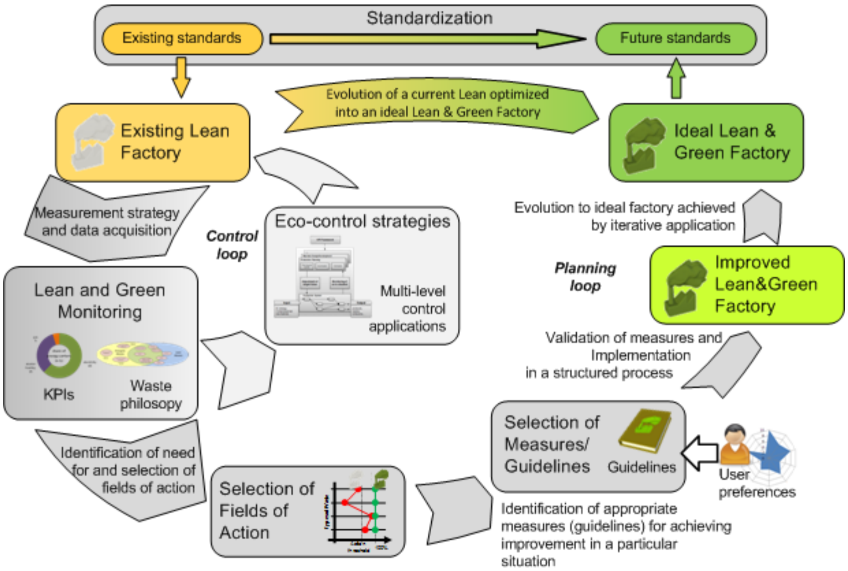


Figure 1: Lean and Green Framework Overview

As the first step of each iteration, lean and green monitoring is conducted for the existing factory, leading to a detailed energetic assessment of the factory or at least a considered part of it.

For factory planning and improvement, in the following step, the given situation is evaluated in terms of energetic wastes for the whole factory or subsidiary parts. Weak points are identified following an approach in which the actual situation in the considered factory is compared with the current state of the art. Areas requiring improvements are identified as Fields of Action (FoA).

Following the identification of FoA, the selection of measures appropriate for achieving improvements in the considered factory is conducted. For this purpose, a standard description format for improvement measures has been defined as the so called lean and green guideline standard. Resulting from this step, the user of the framework gets a structured list of guidelines which should be implemented in the considered factory.

Besides the planning loop described above, a control loop is implemented in the lean and green framework, responsible for managing the operation phase of a factory (e.g. controlling process parameters of machinery on the shop floor). Factory control secures the operation of the whole production in the state it was defined for via the application of so called eco-control strategies. To a certain extent, this control loop is based on the same data and information gathered during energy profiling (e.g. the real time energy value stream analysis – see section 2.2), especially concerning continuous data acquisition on production and technical building equipment.

2.2 Lean and Green Monitoring

With the given motivation and background of energy and resource consumption (improvement) in manufacturing companies, the developed method of lean and green monitoring focuses on providing a higher level of energy and resource flow transparency in production environments. The method has been developed based on a set of known methods that have been applied singularly in several case studies in different industry sectors. These methods have now been integraded in a step-by-step procedure which starts from a macroscopic pespective on a given production environment (e.g. a complete factory or a single production line).

Top down approach within the holistic perspective

The top down approach can be understood as the initial step when focussing on an existing brown field site. The approach consists of three steps: prioritisation of energy carriers used in the factory; creation of an energy portfolio to combine already present nominal power data from energy transforming machines and installations, equipment and devices with simplified time studies; mirco analysis of single most impacting entities to derive their energetic “consumption” behaviour.

Prioritisation of energy carriers and usage profiles

In order to focus on the most relevant energy forms, a physical (joules), economical (€) and ecological (CO2 eq.) assessment of the energy throughput of external supplied energy carries such as electricity, gas, district heat etc. has to be conducted. A possible data basis for that is represented by billing documents and load profiles on 15 minute time base, availabe from the energy provider. Therfore no metering jobs are required at this step. Based on that data a first evaluation can be performed which provides a prioritized procedure for follow-up actions.

Energy portfolio

With the most relevant energy carriers at hand, the second step is to identify the most relevant energy transition processes (consumers) of the most relevant energy carriers with the highest identified saving factor (costs or ecological impact). As described by Thiede [4] the energy portfolio analysis can be performed initially by collecting nominal values (connected load) and estimated utilization times only as visualized exemplarily in Figure 2. The collected individual values from all entities transforming the addressed energy carrier are placed in a portfolio with the connected load on the y-axis and the estimated utilisation rate on the x-axis. The mean connected loads and the mean utilization rate form the horizontal and vertical separators for the four quadrants of the energy portfolio. Furthermore, the energy portfolio gives involved stakeholders a decision basis for qualifying entities for a continuous energy monitoring due to their leverage factor on energy costs either through runtime (quadrant IV) or power demand (quadrant II) or both (quadrant I).

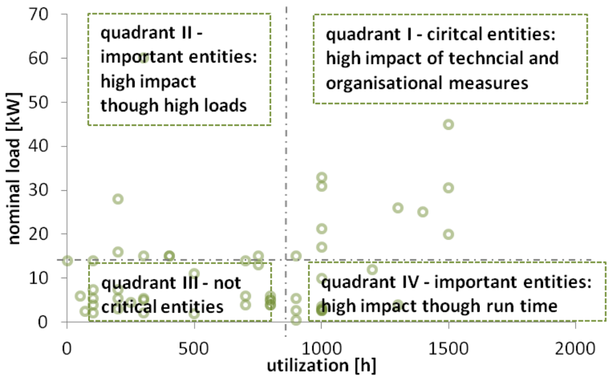


Figure 2: Energy portfolio analysis (example).

Micro Analysis of Entities

A detailed analysis of energy transforming entities (consumers) can be very time intensive. Therefore, the before mentioned prioritisation is necessary. The prioritisation is done on a basis of present data or data that is easily accessible e.g. through technical (electrical) specifications or documentations as well as production plans and expert knowledge. The first prioritisation basically defines the relevance of the entity with regard to their energetic impact in the factory (selected system boundary). Entities with a low relevance (quadrant III of the energy portfolio) should be excluded in the first run. The high prioritised entities are now evaluated regarding to their descriptiveness of their energy demand. Highly dynamic interdependend production process are energetically fairly difficult to describe with reference to a specific discrete product flow. Therefore, a continuous energy monitoring is recommended in order to calculate energetic performance indicators such as the specific energy intensity. On the other hand, if results from single energetic measurement series can be reproduced or at least be described in correlation to product and operating parameters, a continuous measurement is not necessary (virtual metering from energetic models).

From static to dynamic evaluation methods and tools

As part of the best available production system evaluation tools identified in literature studies, e.g. the the Energy Value Stream Analysis (EVSA), as introduced by Erlach [14], have been identified to be suitable for the evaluation of existing brown field process chains. When extended by process energy demands from peripheral processes and technical building services as done by Bogdanski et al. [15], the methodology meets the requirements of the holistic perspective.

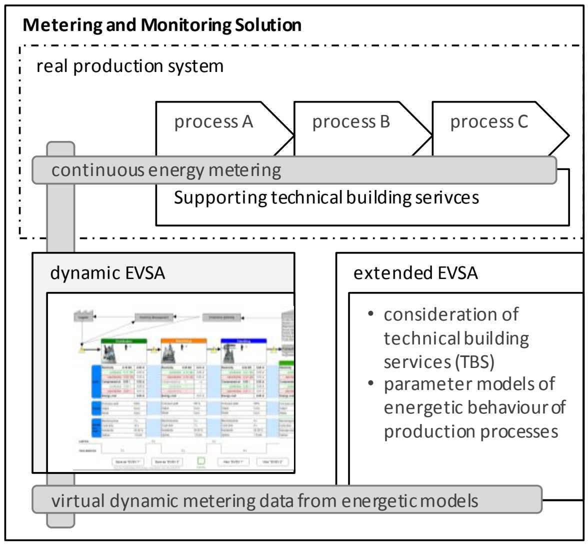


Figure 3: Concept of the dynamic EVSA supported by the realtime metering and monitoring solution.

As depicted in Figure 3 the static extended EVSA method is fed from two realtime (dynamic) data sources. Virtual metering data from mathematical models derived from single measurement and continuous physical data from various energy flow sensors in the field (real production system). With this new dynamic evaluation method based on an industrial hardware solution (metering and monitoring of relevant energy flows in the process chain), an adhoc transparency and live evaluation of conventional, throughput and material flow oriented, production paramters (lean) and energetic as well as environmental (green) becomes possible. This developed tool provides a basis for adhoc descion making and quick evaluation of applied improvement measures from a holistic perspective. The EVSA can thus be used to enhance the machine and factory oriented perspective of the energy portfolio analysis with the cost and process oriented view.of value creation.

2.3 Identification of Fields of Action

After the acquisition and preparation of energetic consumption data during Lean and Green Monitoring (compare Figure 1), in the following step relevant improvement potentials have to be identified in order to derive, in a third step, relevant FoA. Potentials (or wastes) can be identified by mapping an entity of interest (e.g. an electrical consumer) with different categories (or reasons) of

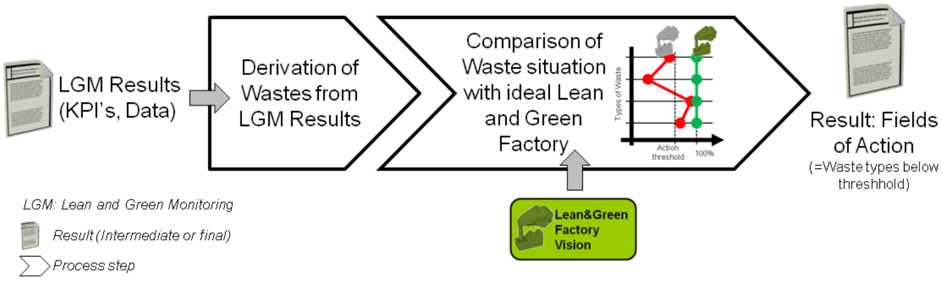


Figure 4: Identification of Fields of Action in the Lean and Green Framework

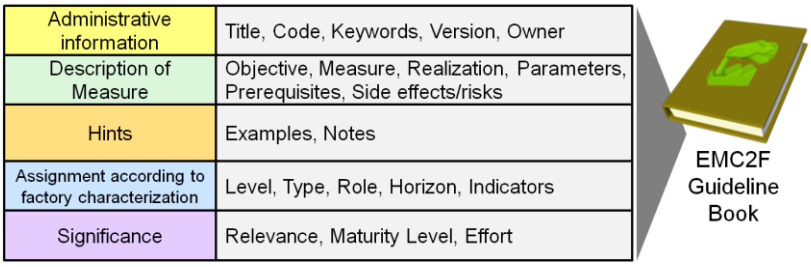


Figure 5: Lean and green guideline structure overview

waste and then comparing the current status quo of the entity with an ideal state. The comparison is conducted individually for each category. Based on these potentials, in the succeeding step, FoA are derived and appropriate measures for severe improvements within a factory are identified and selected for implementation. In a first approach the following categories of wastes were defined from an electrical consumer's (transforming entity) perspective:

- improper consumer design (i.e. an alternative design for the consumer exists that is fulfilling the same requirements consuming less energy e.g. using pneumatic tools instead of electric ones)
- improper consumer utilization (i.e. the way the consumer is utilized/controlled – manually or automatically – is not ideal in terms of minimum energy consumption, e.g. conveyor belts that are moving permanently and not only when required)
- improper requirements, constraints (i.e. external requirements or constraints that define the design/utilization and thus the consumption of the transformation processes are improperly defined when compared with the actual requirements that are necessary to execute the value adding processes of the value stream)
- inefficient supply of resources (e.g. missing opportunities for heat recovery or leakages in a supply with pressurized air)

Excessive energy consumption can either directly be caused by the transformation processes of the consumer itself or by secondary effects induced by the consumer's behavior increasing the energy consumption in other parts of the factory (e.g. the excessive use of a ventilation system not only requires the electrical energy for the fan itself but can also cause an excessive operation of the heating system).

The ideal state can for example be derived from current state of the art machines, logical reasoning or from alternative waste concepts like the seven "Lean-Wastes" [9]. It gives a good indication on which areas to focus on when trying to minimize energetic consumption. For example, the ideal state in terms of lighting-control is achieved when lighting intensity is always adjusted immediately to the lighting requirements given at each area of a building. Potentials are described relatively in comparison with the ideal state and thus an absolute saving potential (e.g. in kWh/year) can be estimated by multiplying the distinct relative numbers with the overall yearly energy consumption derived from the portfolio analysis. Furthermore, by using relative numbers, the identification of potentials and the Lean and Green Monitoring, can be executed independently from each other.

Using normalized values as the basis for comparison (e.g. percentage of achievement of the ideal factory's score), a ranking of the different waste types is achieved. Including a threshold, defined in relation to the ideal score values, waste types showing a high deviation from the ideal values are used to identify fields of action. The whole sub process for deriving fields of action is depicted in Figure 4. Further examples for the categories of waste are listed in section 3.2.

2.4 Lean and Green Guidelines

Measures as Guidelines

Within the Lean and Green Framework, each relevant measure is described as a guideline, concentrating the core knowledge on how to implement the measure in general, thus naming the objective, implementation steps as well as main influences of a measure in a standardized way. Further, also the main information for a proper identification of a guideline in a particular case is to be provided per measure in a standardized way, e.g. by listing the particular performance indicators improved by the specific measure, or the factory level targeted by the measure. An overview of the guideline structure is given in Figure 5.

Guideline Selection Process

For the selection of appropriate measures for dedicated improvements of a factory in relevant fields of action, a process for stepwise narrowing down applicable guidelines is

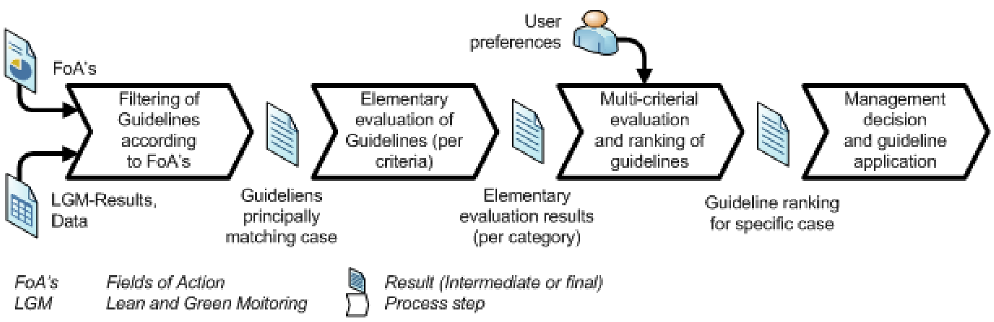


Figure 6: Guideline Selection Sub-Process

introduced (Figure 6). In the first step, guidelines matching the identified Fields of Action are filtered from all available guidelines. All the guidelines are selected whose target areas address the required fields of action/energetic wastes / KPIs. The result is a collection of all guidelines that could generally improve the identified fields of action. However, at this point, no consideration has been given to how well a guideline fits the given situation, e.g. in terms of improvement potential, but also in terms of applicability.

Thus, in a second step, all pre-filtered guidelines are evaluated according to criteria which influence the applicability as well as the expected outcome, separately for each criterion. Examples for these criteria are the effort for application (e.g. time or budget), KPI-improvement-potential, or the level of maturity of the guideline. The evaluation is conducted by the user of the overall framework, using the facts from the guideline sheet as a basis for his estimation. Additional information may have to be acquired during the evaluation (this might happen on different levels/with different effort, e.g. additional information might be sourced on a website or from a supplier).

After the elementary evaluation of each guideline, the results have to be transformed into one overall score for each guideline, representing the applicability and building the criteria for the later selection of the guideline. At this point, the framework user will define preferences which influence the calculation of the overall score, allowing the user to foster different strategies, e.g. a more ecological or more economical strategy. Thus, the user preferences are acquired as a pair wise weighting of the different criteria the guidelines have been evaluated in. A final score indicating the applicability as well as improvement potential for each guideline in the particular case is calculated, allowing a ranking of the guidelines. Thus, the most appropriate guideline to be applied can be selected easily. At this point it is possible to take into account multiple rankings, e.g. for comparing a strategy focusing on economical with one focusing on ecological performance.

After the selection of one or several guidelines, in the following step the application of the measures described in the guideline has to be performed. From the perspective of the overall lean and green framework, this step is represented as one process step. Thus, the framework process restarts after the implementation with the next iteration.

3 USE CASE

3.1 Pilot Description

The lean and green framework has been tested in a pilot application in an existing factory of the Siemens AG. The focus for application was laid on one building within the factory that is considered a bottleneck for the overall value stream of the plant as well as a hot spot in terms of energetic consumption. Various production processes take place (e.g. welding, milling, grinding and inspection) in a job shop like arrangement in manual as well as in fully automatic form. Due to the high weight of the products and the dense arrangement of workstations material transport is challenging and time consuming. Due to the different production processes different requirements in terms of technical building services (TBS) exist (e.g. ventilation of air, lighting, heating, pressurized air) that vary throughout the day. Hence, a systemic and scientific approach for fostering all energy saving opportunities as well as taking possible trade-offs with traditional production targets into account is required.

3.2 Application of Framework

Following the respective steps of the overall lean and green framework, as depicted in Figure 1, the Lean and Green monitoring was performed for the aforementioned building and its processes. The main energy carriers identified are electricity, pressurized air and district heating. An initial energy portfolio analysis based on nominal data and operation times was performed. Focusing on the transforming processes in quadrant 1 of the energy portfolio (critical entities) three consumers were selected for a detailed analysis: lighting- and ventilation system and the milling machine with nominal loads ranging from 30 to 160 kW. Detailed load measurements were performed on these three entities. In order to derive improvement potentials/wastes from the overall energy consumption of the selected entities, the waste approach, described in Section 2.3, was applied, taking into account further organizational information, requirements and building data. Exemplarily the further application of the framework is shown for the lighting system.

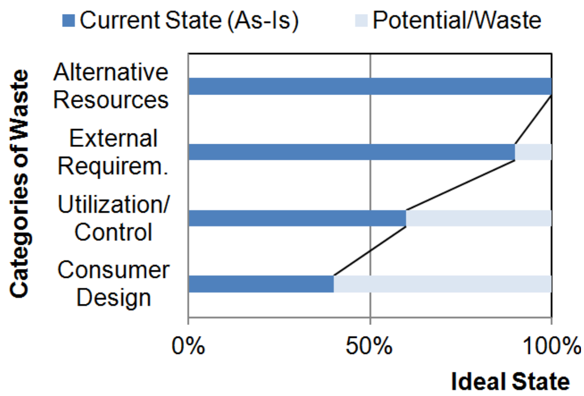


Figure 7: Improvement potentials for lighting system

The improvement potentials for the lighting system within the different categories of waste are shown in Figure 7. Based on the evaluation of potentials several measures for minimizing the energy consumption of lighting systems were proposed:

- automatic control techniques based on sensor systems like motion sensors, brightness sensors, time switches (FoA: TBS-Control)
- improving manual control of the lighting system by employee awareness, incentive systems, feedback signals, (FoA: Employee, Training)
- minimization of space requirements by an optimized building layout that allocates production processes with the same lighting requirements in the same areas (FoA: Layout Planning)
- minimization of time requirements for example by an optimized production schedule with the main objective to avoid additional working shifts. Other systemic methods like TQM, TPM that minimize rework and non-productive-time, may have the same effect. (FoA: Production Scheduling, Production Planning)
- replacement of the current fluorescent tubes (T8 with conventional ballast) with modern systems like electronic ballasts with T5 configuration or LED tubes (TBS-Design)

The proposed measures were evaluated among different categories indicating the applicability and effectiveness of each measure. Evaluation within the different criteria was based on expert interviews and simple models. A one-dimensional ranking of the measures can be achieved by a weighting of the different criteria using multi-criteria decision analysis like Analytic Hierarchy Process, Analytic Network Process or a simple value analysis. The results of the evaluations are depicted in Figure 8 indicating that several of the proposed measures might be applicable depending on strategic preferences of production management.

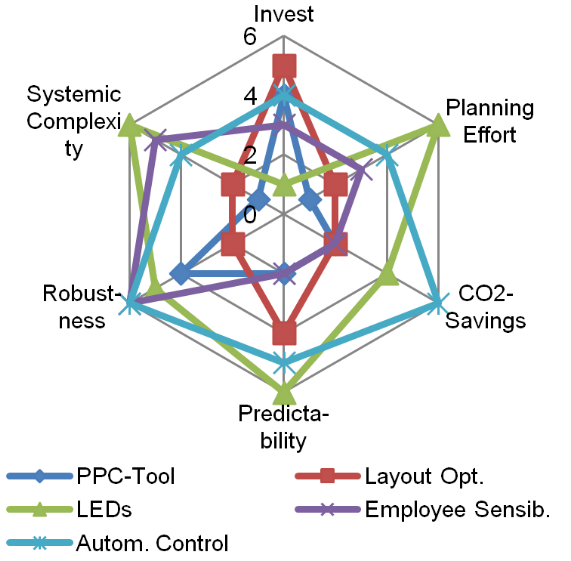


Figure 8: Evaluation of improvement measures for minimizing lighting consumption (scale of 0-6 with 6 being the best)

4 CONCLUSION & OUTLOOK

Increasing the energy efficiency of manufacturing companies has been identified as one of the major goals for today's industrial environment. A large and still growing amount of possible measures for achieving this goal has become available from research and development. However, a wide implementation of such measures is often hindered by difficulties in identifying appropriate measures for specific situations, or by sometimes conflictive goals in comparison with conventional, economically driven objectives. For overcoming this shortage, responsible functions in factories – like production planners, equipment designers or maintenance units – need methodological support, providing guidance in identifying and selecting appropriate measures even if the person responsible is not an expert in energy efficiency.

In this paper a generic framework has been introduced that supports this identification of energy efficiency potentials and the selection of appropriate measures in the context of discrete manufacturing environments. Future research will concentrate on a stronger implementation of the lean aspects within the selection processes as well as concretizing and formalizing the single steps within the framework, so that less effort for application is required. Furthermore, the generic categories of waste will be specified based on the respective objects of interest allowing a more precise and quicker derivation of adequate measures in a specific case.

5 ACKNOWLEGMENTS

This research activity has been financed by the European FP7-NMP project 'EMC²-Factory' (www.emc2-factory.eu).

6 REFERENCES

[1] Herrmann, C., Thiede, S. and Heinemann, T., 2011, "A Holistic Framework for Increasing Energy and Resource Efficiency in Manufacturing." Advances in Sustainable Manufacturing. Springer Berlin Heidelberg. 267-273.

[2] Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S. et al., 2012, Towards energy and resource efficient manufacturing: A processes and systems approach. In CIRP Annals - Manufacturing Technology 61 (2), pp. 587–609.

[3] Mose, C., Weinert, N. 2013, Evaluation of process chains for an overall optimization of manufacturing energy efficiency; Paper accepted for publication at the 23rd International Conference for Flexible Automation & Intelligent Manufacturing, June 26-28, 2013, p. tbd., Portugal

[4] Thiede, S., 2012, Energy Efficiency in Manufacturing Systems, Springer, ISBN 978-3-642-25913-5

[5] Weinert, N., Chiotellis, S., Seliger, G., 2011: Methodology for planning and operating energy-efficient production systems. In CIRP Annals - Manufacturing Technology 60 (1), pp. 41–44.

[6] Fischer, J., Rohrmus, D., Weinert, N., 2012, Investigation on adapting production strategies for a Smart Grid environment, Proceedings of the 10th Global Conference for Sustainable Manufacturing, Oct. 31st – Nov. 2nd, 2012, Istanbul, Turkey,p. 611-616.

[7] Abele, E., Sielaff, T., Beck, M., 2012, Konfiguration energieeffizienter Werkzeugmaschinen. In: Werkstattstechnik online : wt, Springer VDI Verlag, Düsseldorf, 102 (5) pp. 292-298. ISSN 1436-4980

[8] Hesselbach, J., Herrmann, C., Detzer, R., Martin, L., Thiede, S., Lüdemann, B., 2008, Energy Efficiency through optimized coordination of production and technical building services; Proceeding of the 15th Conference on Life Cycle Engineering, Sydney.

[9] Ohno, T.; Toyota production system: beyond large-scale production. Productivity Pr, 1988

[10] Monden, Y., Toyota production system: an integrated approach to just-in-time. Productivity Pr, 2012.

[11] Bergmann, L.: Nachhaltigkeit in ganzheitlichen Produktionssystemen; Vulkan-Verlag, 2009.

[12] Diaz-Elsayed, N., Jondral, A., Greinacher, S., Dornfeld, D., Lanza, G., 2013: Assessment of lean and green strategies by simulation of manufacturing systems in discrete production environments. In *CIRP Annals - Manufacturing Technology*.

[13] Dües, C.M., Tan, K.H., Lim, M., 2011, Green as the new Lean: how to use Lean practices as a catalyst to greening your supply chain., In Journal of Cleaner Production 40, pp. 93–100.

[14] Erlach, K.; Westkämper, E. (Eds.): Energiewertstrom Der Weg zur Energieeffizienten Fabrik Fraunhofer IRB Verlag, Stuttgart, 2009

[15] Bogdanski, G., Schönemann, M., Thiede, S., Andrew, S., Herrmann, C. 2012: An Extended Energy Value Stream Approach Applied on the Electronic Industry, In: Proceedings of the International Conference on Advances in Production Management Systems (APMS), Rhodes, Greece, 2012

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

15.3 Smart Manufacturing Execution System (SMES): The possibilities of evaluating the sustainability of a production process

J. Larreina [1], A. Gontarz [2], C. Giannoulis [3], V.K. Nguyen [4], P. Stavropoulos [3], B. Sinceri [5]

[1] Industrial Management and Innovation Unit, IK4-Tekniker, Spain

[2] Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology, Switzerland

[3] Laboratory for Manufacturing Systems and Automation (LMS), University of Patras, Greece

[4] CADCAMation SA, Switzerland

[5] Process Research Department, Centro Ricerche Fiat, Italy

Abstract

Sustainability in production processes is mandatory in the manufacturing environment due to restrictions such as legislation. Conventional Manufacturing Execution Systems (MES) don't really support environmental sustainable goals but are actually the most suitable background for an extension towards sustainability monitoring, control and assessment. This paper introduces a new MES generation which is enhanced with interoperable data acquisition, analysis and optimization in line with sustainability goals.

A harmonization work on metrics and indicators, aligned with the Triple Bottom Line, is presented based on an analysis of industrial users' requirements within machining process context. Also, a framework for sustainability evaluation through a specific architecture is introduced.

Based on an industrial use case, the given approach is set in the context of the FoFdation project which also addresses the integration among manufacturing IT systems towards overall lifecycle management.

Keywords:

Data acquisition, Green manufacturing, Manufacturing Execution System (MES), Sustainability evaluation, Triple Bottom Line

1 INTRODUCTION

Sustainability in production processes is mandatory in the manufacturing environment due to constraints such as legislation, market and company goals. The market factor explains why there is a growing need for better monitoring and awareness of manufacturing processes to address both environmental and productivity optimization issues. Quality improvement, production cycle reduction must nowadays be managed while also taking into account new concurrent thresholds such as energy consumption and carbon footprint indicators.

Conventional Manufacturing Execution Systems (MES) don't really support environmental sustainable goals but are actually the most suitable background for an extension towards sustainability monitoring, control and assessment. This paper introduces a new generation of MES which is enhanced with interoperable data acquisition, analysis and optimization in line with sustainability goals.

A harmonization and clarification work on metrics and indicators, aligned with the Triple Bottom Line, is presented based on the analysis of industrial users' requirements and literature research within machining process context. Furthermore, a framework that suggests how to implement sustainability evaluation through a specific architecture and the required metrics description is introduced.

The given approach, based on an industrial use case, is set in the context of the FoFdation project (www.fofdation-project.eu) which also addresses the integration with PLM-ERP towards overall lifecycle management.

The paper introduces an analysis and proposal for a sustainability evaluation framework in which the IT solution is based. A comprehensive set of existing sustainability metrics and indicators have been considered and categorized according to different aspects such as the Triple Bottom Line definition. Out of such metrics and indicators, the framework was chosen to foster the implementation of sustainability improvements and support decision makers in assessing the impact and effects of these measures not only on the environmental requirements but also on the overall business performance.

After a review on existing commercial systems (dedicated data collection tools, MES like tools and specialized systems for energy management), the Smart Manufacturing Execution System (SMES) solution is presented. The conceptual idea for such a solution was based on a conventional MES, adapted and enhanced with new hardware architecture in order to directly collect information on resource consumption from the machines. The proposed architecture allows for the combining of information on the execution of the manufacturing operations and resource consumption data, leading to an improved awareness of the manufacturing operations performance. The data collection features are completed with an analysis through an Online Analytical Processing (OLAP) system which allows the investigation of sustainability parameters in a multidimensional space, and then the optimization of the production by a scheduler that schedules production orders according to an energy efficiency strategy.

The resulting prototype was set up as a demonstrator in the Centro Ricerche Fiat (CRF) labs for validation purposes of SMES data collection features and details of this validation are given below.

As a conclusion, the difficulties which were encountered during the implementation and installation are stated and the challenges for the future mentioned. The results obtained

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

allow to explore new concepts for online and automatic optimization towards a sustainable manufacturing process.

2 SUSTAINABILITY EVALUATION FRAMEWORK

2.1 Metrics and indicators

Sustainable manufacturing and related energy efficiency are becoming an important topic in industry. Still, in the case of energy efficiency, neither machine tool users nor builders have a clear picture of their energy use in production [1, 2]. This fact is due to individual evaluation approaches which are dependent on the field of industry, motivation, and individual manufacturing processes and needs; the Ford Product Sustainability Index (PSI) [3], for instance, defines a set of indicators based on the ISO 14040 (Life Cycle Assessment - LCA). Those indicators are selected from the point of view of the automotive industry. A common approach on a higher aggregated level is given by the Global Reporting Initiative (GRI) [4]; as this method is globally recognized and is supposed to be generally valid, but it is also controversially discussed [5]. Another large scale approach is given by the Sustainable Value [6]; it evaluates the resource allocation and its effects in money units for economical, ecological and social resources in line with the Triple Bottom Line definition. These examples illustrate various selections of metrics and indicators for the evaluation of sustainability with their dependencies, individual needs and information and levels of application, e.g. LCA or organizational levels, as indicated by [7-9]. Based on this application variety a selection tool was developed by the FoFdation project where more than 120 indicators and metrics were grouped together according to three aspects in order to support users' selections: Life Cycle Assessment status, application level within the factory and the Triple Bottom Line definition. This grouping has led to key performance indicators (KPIs), Environmental Performance Indicators (EnPIs) and Measurement Values (MVs) (Figure 1) and enables various users to set their metrics.

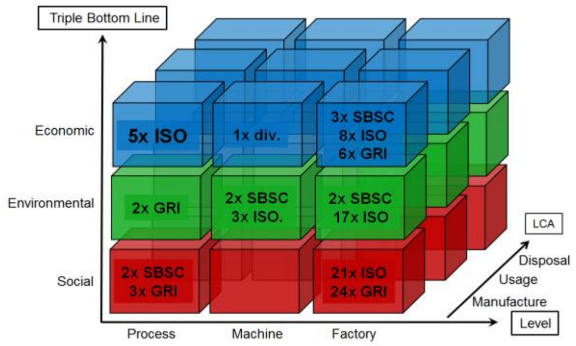


Figure 1: Clustering of metrics and indicators within the FoFdation project

As the strategic level mainly focuses on awareness and control and is dependent on the CRF use case, special focus for metrics and indicators was given on the shopfloor for machine tool energy evaluation according to ISO14955 [10].

2.2 Sustainable performance measurement

As the assessment of the sustainable performance in the field of energy efficiency in production has become a major asset in manufacturing, Bunse et al. [11] concludes that various energy efficiency performance measures already exist in the aggregated sector, e.g. plant, but these performance measures are not necessarily suitable to assess energy efficiency performance of single manufacturing processes or the machine tool. Furthermore, appropriate energy efficiency metrics and measurement frameworks on machine, process and plant level, and energy efficiency benchmarks on machines and equipment for monitoring and optimization are missing. Emerging new sensor technologies and smart embedded devices enable operation based process measurements and therefore can provide accurate information for monitoring the production performance, Karnouskos et al. [12].

In the FoFdation project a framework was chosen that is able to integrate energy efficiency measures in an adequate performance assessment system for manufacturing companies on the shopfloor level. This approach can foster the implementation of energy efficiency improvements and support decision makers in assessing the impact and effects of energy efficiency measures not only on the environmental requirements but also on the overall business performance.

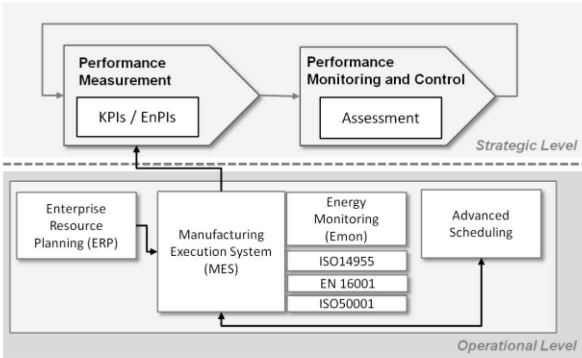


Figure 2: Elements of Sustainable Evaluation Framework in the FoFdation project based on Bunse et al. [11]

3 SMART MANUFACTURING EXECUTION SYSTEM

The SMES aims for leveraging an existing MES to reduce the economical and environmental impact in manufacturing through reducing cycle times, rework, materials, energy, emissions, wastes and scraps.

3.1 State of play in data collection systems

Sustainability evaluation must lie on a proper IT system for data collection. A review on commercial solutions reveals three main kinds of systems devoted to such a purpose: dedicated data collection tools, MES like tools, and specialized systems for energy management.

Most dedicated data collection tools focus only on data monitoring and availability. Their objective is to deliver the information, store it in a base, and visualize it through tables, graphs and reports, e.g. Predator MDC™, RF-SMART, Scytec Hosted DataXchange™, IntegraNet™, Acumen's Automated Shop Data Collection SW, Catalyst PDC™, Q*ADC, etc. They typically use standard database and/or spreadsheet formats for storage and they collaborate with MES and ERP systems for delivering the requested data.

Higher level MES like tools focus mainly on the product/assets information collection such as product tracking information, BOM, assets utilization, equipment states, resource availability, etc., e.g. EZ-MES. Some of these tools go beyond production data collection and reporting as they provide some extra modules/functions that support semiautomatic scheduling and 'what if' scenarios, e.g. FACTIVITY, Litum, Acumen's Job Tracking SW.

Specialized systems that focus on sustainability issues are also available from several manufacturers. Most of the systems focus mainly on energy management, although they may also support other sustainability metrics (e.g. Schneider Electric, Siemens WinCC, Rockwell Automation EEM, GE Energy Management).

As a consequence of the analysis performed, an existing conventional Manufacturing Execution System (MES) has been selected as a basis for the adopted solution within the FoFdation project context. Although not fully compliant with sustainability requirements, traditional Manufacturing Execution Systems are recognized as the most appropriate solutions towards a comprehensive approach for sustainable monitoring, controlling and assessment [13].

The selected MES has been adapted and improved with a new system (FoF-EMon) that enables the data collection and monitoring of environmental resource consumption on the machine tool. The combination of the MES and FoF-EMon results in a package that relates information on the execution of the manufacturing operations to environmental resource consumption data. Such a combination leads to an improved awareness of the manufacturing operations performance through a configurable set of sustainability KPIs.

3.2 Architecture

In the figure below, the architecture for the conceptual solution of SMES is shown.

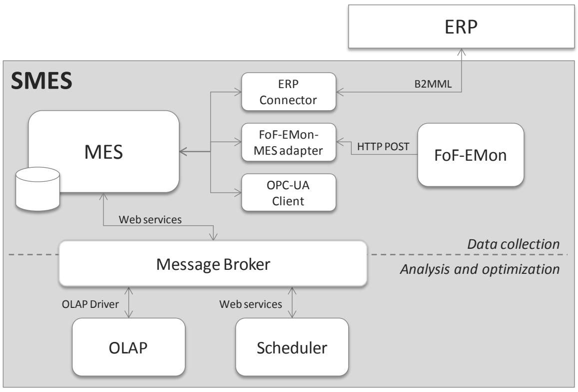


Figure 3: SMES Architecture

The architecture includes a centralized integration point (Message Broker) which coordinates the information flow among all modules within the SMES. It consists of an interoperable platform that operates through Web Services and SOAP protocol and utilizes a message driven mechanism for information exchange. Key elements in the architecture are those related to data collection and analysis and optimization. As part of data collection, the existing conventional MES is devoted to collect manufacturing operations execution data from the shopfloor. It incorporates specific modules to provide higher connectivity with other systems, i.e. the ERP connector to integrate with the ERP, and an OPC UA client to give the SMES the capability to connect to any system that supports this *de facto* communication technology standard. An adapter relates the MES to FoF-EMon which collects data directly from the machine tool components with internal and external sensors and combines simulations too to save costs on the applied sensors. FoF-EMon monitors the consumption of the different parts of the machine tool and provides categorized information for the shopfloor.

Regarding analysis and optimization, the architecture includes a feature for Online Analytical Processing (OLAP) which allows the consolidation and analysis of sustainability data collected on the shopfloor in a multidimensional space, based on the SMES database, and a scheduler to schedule production orders according to an energy efficiency strategy. Based on operations research and artificial intelligence, it applies a newly developed dispatching rule, Less Energy Consumption (LEC), that allows production schedules to be obtained that lead the enterprise to operate on the lowest energy consumption possible.

3.3 Environmental sustainability data collection

A key element for energy efficiency evaluation and optimization is seen in the accurate quantification of the energetic behavior on the shopfloor, machine tool level [8, 14, 15] and its components. For this reason a data acquisition tool for Energy Monitoring (FoF-EMon) on the machine tool as part of the Smart Manufacturing Execution System (SMES) was developed within the FoFdation project. FoF-EMon is understood as a crosslink between machine control and the Manufacturing Execution System (MES). Based on ISO14955 [10], FoF-EMon collects all relevant energetic information, including electrical components and compressed air and media flow from external sensors and from the machine tool control and simulations for a detailed resource evaluation. With a sampling rate of 5Hz all energetic relevant information, including peak power, are collected, synchronized and displayed (Figure 4). This data is then processed, analyzed and transmitted with a constant rate of 1Hz to the MES.

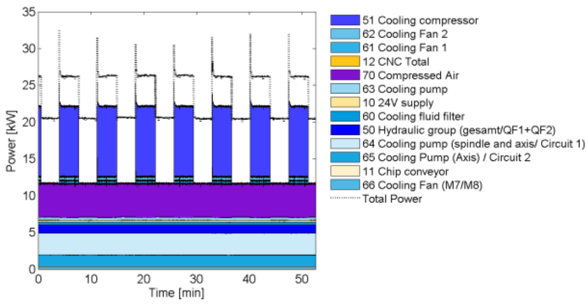


Figure 4: Example of data provided by FoF-EMon

3.4 Production execution data collection

For the collection of production execution data an MES system has been adapted. The MES is able to collect essential data (work order, actual times and quantities, machine failures and times incurred, traceability data, quality data, etc.) both automatically and manually through an HMI on industrial PCs on the shopfloor, and incorporates data coming from the machine through the FoF-EMon. The FoF-EMon-MES adapter provides information on resource consumption (energy, compressed air) from the FoF-EMon. This information is aggregated and stored in the SMES database for subsequent analysis. The consumption information is stored by time, piece, event/machine status, but also in relation to work order, part number, material (traceability) and process (how it was machined). This aggregation facilitates the analysis that relates energy consumption data with production data which is then presented through an OLAP based dashboard that shows relevant KPIs with their target and actual values.

Nevertheless, the MES itself also has the ability to analyze the performance of the production site in terms of sustainability through sustainability metrics and PIs. The MES includes a dashboard where the operator and line responsible staff can check the status of sustainability performance in a certain machine. It contains information on the production order, its status, metrics and PIs to assess the performance: processing times, setup times, downtimes; produced quantities (good, scrap, and their causes); energy consumption (categorized by compressed air, machine conditioning, machining, process cooling and conditioning, waste handling, tool handling); and several indicators such as OEE, availability, performance and quality or the energy consumption ratio (relationship between energy used for machining compared to the energy for auxiliary systems), which gives an idea of the effectiveness of the machine tool and the efficiency of the energy used.

In order to collect data on the shopfloor, information from the ERP related to the scheduled work orders has to be obtained by the MES. It also needs to feed back the ERP with information of actual production data collected on the shopfloor. Such information is exchanged through a developed ERP connector based on Business To Manufacturing Markup Language (B2MML) schemas, the XML implementation of the ANSI/ISA-95 family of standards, known internationally as IEC/ISO 62264. In addition to this, the MES includes a work order sequencer to enable it to change the production schedule downloaded from the ERP or from the scheduler within the SMES, due to last minute changes (emergencies, lack of resources or material, etc.).

The MES also includes an HMI for production supervision. The corresponding HMI shows the lines and machines under control and gives quick information on the status of the machines, but also detailed information on sustainability performance for each machine on the shopfloor.

3.5 Analysis and optimization

The collection of data for further analysis at a later point in time requires the use of a repository with a structure to support a significant amount of data per machine tool. Implementation of this approach to a larger production scale that will lead to the big data problem is not considered in this paper. In this approach, the collected data are applied to the identified sustainability metrics and act alongside decision support systems. Moreover, the resulting values can be further visualized in dashboard applications or by using commercial spreadsheet applications to perform personalized analysis. The metrics values are accessible by other systems such as the IMPACT scheduler to optimize the plan of the next period based on the energy consumption of the last production period.

This chapter shows the SMES approach for analysis of the collected data through OLAP and for the optimization of sustainability at different levels; at machine level (micro-optimization) with FoF-EMon and at production line level with a scheduler (macro-optimization).

Online Analytical Processing (OLAP)

The amount of data is quite significant and restricts the selection of the storage system. Online Analytical Processing (OLAP) tools are the foundation of data warehouses [16, 17] supporting analysis of enormous amounts of data in rational response times. In this paper we considered the Relational OLAP (ROLAP) variation as production performances are stored in a traditional Relational Database Management System (RDBMS). Furthermore, the lowest level of production information is considered to be the collected information from the machine tools. OLAP tools structure information in cubes consisting of dimensions, measures and facts. The cube is organized as follows. There are 8 dimensions: (D1) machine tool extends to the hierarchical levels [18], (D2) part, (D3) operation, (D4) work orders, (D5) operators, (D6) time (D7), machine components and (D8) machine status, and 4 facts: (F1) cycles of machine tools including yield quantities and processing times, (F2) energy consumption of each machine function, (F3) production demand and (F4) machine statuses. Table 1 indicates the number of measures implemented in each fact table. Additionally, 22 calculated measures of aggregate raw data i.e. Overall Equipment Efficiency (OEE), Machine Utilization and Machine Efficiency.

Table 1: Facts and Measures

#	Fact	Measures
F1	Machine Cycles	4
F2	Machine Energy	11
F3	Machine Status	5
F4	Machine Power	4
F5	Production Demand	4

This implementation gives us the opportunity to correlate measures such as availability of machines with Mean Time to Repair (MTTR) as shown in Figure 5 more efficiently, or correlate the energy consumption of a factory with the demand volume or the Quality Ratio of facilities. Moreover, the potential to explore the correlation possibilities is left to the end user by selecting the appropriate measures for visualization from dashboard however, the dashboard itself is not included in the current paper.

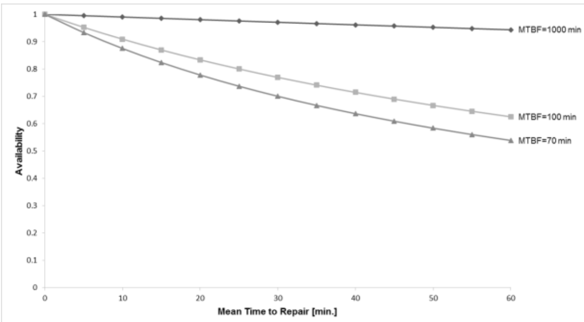


Figure 5: Availability as a Function of Mean Time To Repair [18]

FoF-EMon

For micro optimization, standby monitoring was introduced in the FoFdation project. As the energy used in machine standby can raise up to 43% of the total energy consumed [19], it is essential to address the non value added standby energy consumption which is independent from quality and safety related issues. According to the monitored data and analysis on FoF-EMon certain components can be switched off in conformity with predefined rules. In the given case the cooling compressor indicated in Figure 3 can be switched off after 15 seconds when the machine is in standby without any negative effects on productivity or quality in the given manufacturing process. Further optimization on the micro-optimization level is seen in the predictive service and maintenance by detecting inefficient components according to Gontarz et al. [20].

The presented level of detail in Figure 3 from FoF-EMon can be used not only for micro-optimization, e.g. active machine tool and machine components' switch off [21], but for macro-optimization as well. In combination with higher aggregated information, such as from the MES, optimized production scheduling can be performed.

Scheduler

Production scheduling has been addressed by many researchers over previous decades. Typical scheduling addresses the problem of allocating jobs and tasks to a number of machines. Energy Aware Scheduling aims to optimize either an existing schedule [22] or to follow certain methodology [23] to obtain the minimum possible energy consumption. In this paper, we consider the IMPACT scheduler [18]; a multicriteria scheduler based on MADEMA method [24, 25, 26], as part of the macro-optimization strategy. IMPACT assigns tasks to resources by typical dispatching rules i.e. Shortest Processing Time (SPT), Earliest Due Date (EDD) etc. However, it can produce a schedule based on a multicriteria method with various factors such as cost, quality, flowtime etc. The model of the proposed scheduler has been extended to include the operating and idle power on each machine tool of the production shopfloor. In addition, the energy consumption criterion has been integrated in order to evaluate the energy consumption performance of the schedule. Moreover, we introduce a Less Energy Consumption (LEC) dispatching rule to assign tasks to machine tools based on their estimated energy consumption. Energy aware scheduling minimizes the energy usage and enhances its efficiency.

4 VALIDATION

In a case study, the FoFdation-SMES prototype including FoF-EMon was implemented in the CRF labs on a 5 Axis Milling machine tool. The implementation included the collection of ERP information, machine status and the full details of power consumption of the machine tool components, e.g. pumps, fans, and motors. By knowing the energetic- and control behavior of each machine tool component in combination with production execution and ERP information, quality- and safety-irrelevant components can be controlled by this system. In this context, a cooling compressor switch off message was successfully generated to reduce the power consumption during standby by 12 kW. Together with a reduced air supply, (4,8 kW) an automated reduction of up to 50% on the total machine tool power consumption during standby is possible with no negative effects on productivity or quality. This implementation is seen as a data acquisition and control tool for all relevant sustainable information related to resource consumption on the machine tool, and proves that the system is able to react to and control certain components to not only monitor but actively increase the environmental performance on the shopfloor with related effects on higher aggregated levels as well.

The validation process did not consider the analysis and optimization implementations which will be tackled in a second phase. The case will be extended to several machines in order to deal with the macro-optimization approach.

5 CONCLUSIONS

The presented work is based on a demo approach that has been built in a pragmatic way to clearly highlight a very practical solution as a proof of concept to address an industry use case where the main requirements are the manufacturing planning process optimization, and the efficiency of the energy consumption in production processes. For this a straightforward approach to achieving sustainability goals has been developed through leveraging an existing MES's functionality to manage raw materials and resources, such as energy. The usage of MES systems for sustainability enhancement opens the door to improve and obtain increased gains in resource optimization.

Therefore the adopted solution is ideal for improving resource utilization – not only in terms of using less material but also by providing better information on how those resources should be used. The MES has been enhanced with resource consumption data collection based on a versatile and easy to install system called FoF-EMon, which includes a dashboard to monitor energy consumption. These results are running as a prototype with both the adapted MES system and the FoF-EMon, and their link. This data collection infrastructure is used by the SMES to optimize the usage of resources through the analysis optimization modules.

The main difficulties encountered in the implementation of the data collection system have been the fact that the machine used is a nonstandard machine tool with multiple retrofits and no up-to-date specifications. A future challenge for the FoF-EMon application is a streamlined and market ready setup procedure for individual implementation. Currently this application is seen as a prototype solution which strongly depends on the goal system architecture. Other important issues are affordable sensors, stability and reliability on both the hardware and software side, improved dashboard and further development in the awareness tool according to the ISO14955 and/or others. For the production execution data collection side, represented by the MES, the main challenges are an easier and faster adaptation to customer functional requirements and the usage of its OPC UA interface in a future factory environment where this technology will be widely spread and, therefore, allows for seamless and interoperable resource consumption data collection from any equipment on the shopfloor.

These results allow us to explore new concepts for online and automatic optimization towards a sustainable manufacturing process, taking into consideration all manufacturing factors.

For further progression, the macro-optimization approach will consider not only energy consumption but also other aspects of sustainability according to the Triple Bottom Line, especially, social ones. Also, the SMES validation will be extended to a scenario with multiple machines.

6 ACKNOWLEDGMENTS

The work reported in this paper was partially supported by CEC / FP7 NMP-ICT Programme, 'The Foundation for the Smart Factory of the Future-FoFdation', (FP7-2010-NMP-ICT-FoF- 260137).

7 REFERENCES

[1] Dietmair, A., Verl, A., 2009, Energy Consumption Forecasting And Optimisation For Tool Machines. MM Science Journal, 3:63-67.

[2] Peroni, M., Polignano, V., 2012, CRF Use Case - Internal document of the FoFdation project WP1.2 and WP5.1.

[3] Schmidt, W.-P., 2006, Life Cycle Tools within Ford of Europe's Product Sustainability Index. Case Study Ford S-MAX & Ford Galaxy (8 pp). The International Journal of Life Cycle Assessment, 11/5:315-322.

[4] G. R. Initiative, 2002, Sustainability Reporting Guidelines on Economic, Environmental and Social Performance. GRI, Boston/Issue. 2002.

[5] Marimon, F., et al., 2012, The worldwide diffusion of the global reporting initiative: what is the point? Journal of Cleaner Production, 33/0:132-144.

[6] Figge, F., Hahn, T., 2004, Sustainable Value Added—measuring corporate contributions to sustainability beyond eco-efficiency. Ecological Economics, 48/2:173-187.

[7] Gutowski, T., et al., 2005, Environmentally benign manufacturing: Observations from Japan, Europe and the United States. Journal of Cleaner Production, 13/1:1-17.

[8] O'Driscoll, E., O'Donnell, G.E., 2013, Industrial power and energy metering – a state-of-the-art review. Journal of Cleaner Production, 41/0:53-64.

[9] Melnyk, S.A., Stewart, D.M., Swink, M., 2004, Metrics and performance measurement in operations management: dealing with the metrics maze. Journal of Operations Management, 22/3:209-218.

[10] I.T.W. 12, 2012, ISO14955 Environmental Evaluation of Machine Tools.

[11] Bunse, K., et al., 2011, Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature. Journal of Cleaner Production, 19/6–7:667-679.

[12] Karnouskos, S., et al. 2009, Towards the energy efficient future factory, Industrial Informatics. INDIN 2009. 7th IEEE International Conference on, 367-371.

[13] Rockwell Automation, 2009, Manufacturing Execution System for Sustainability. Extending the scope of MES to achieve Energy Efficiency and Sustainability Goals.

[14] Avram, O., Xirouchakis, P., 2010, Evaluating the use phase energy requirements of a machine tool system. Journal of Cleaner Production, 19/2011:699-711.

[15] Gontarz, A., Weiss, L., Wegener, K., 2010, Energy Consumption Measurement with a Multichannel Measurement System on a machine tool, in International Conference on Innovative Technologies IN-TECH Proceedings of the International Conference on Innovative Technologies, Editor: Prague, Czech Republic. 499-502.

[16] Hsu, K.C. Li, M.-Z., 2011, Techniques for finding similarity knowledge in OLAP reports. Expert Systems with Applications, 38/4:3743-3756.

[17] Prat, N., Comyn-Wattiau, I., Akoka, J., 2011, Combining objects with rules to represent aggregation knowledge in data warehouse and OLAP systems. Data & Knowledge Engineering, 70/8:732-752.

[18] Chryssolouris, G., 1992, Manufacturing Systems: Theory and Practice, New York: Springer-Verlag.

[19] Abele, E., Dervisopoulos, M., Kuhrke, B., 2009, Bedeutung und Anwendung von Lebenszyklusanalysen bei Werkzeugmaschinen, ed. Gabler, Wiesbaden: Springer.

[20] Gontarz, A., et al., 2013, Machine tool optimization strategies for ecologic and economic efficiency. Journal of Engineering Manufacture 2013, 227/1:54-61.

[21] Gontarz, A., et al., 2013, Standby Indication and Energy Management on Machine Tools, in ICT for Sustainability - The Challenge of Making It Real, Zürich.

[22] Bruzzone, A.A.G., et al., 2012, Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops. CIRP Annals - Manufacturing Technology, 61/1:459-462.

[23] Weinert, N., Chiotellis, S., Seliger, G., 2011, Methodology for planning and operating energy-efficient production systems. CIRP Annals - Manufacturing Technology, 60/1:41-44.

[24] Chryssolouris, G., Chan, S., Cobb, W., 1984, Decision making on the factory floor: An integrated approach to process planning and scheduling. Robotics and Computer-Integrated Manufacturing, 1/3–4:315-319.

[25] Chryssolouris, G., Chan, S., Suh, N.P., 1985, An Integrated Approach to Process Planning and Scheduling. CIRP Annals - Manufacturing Technology, 34/1:413-417.

[26] Papakostas, N., et al., 2010, An approach to operational aircraft maintenance planning. Decision Support Systems, 48/4:604-612.

11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

15.4 Increasing energy efficiency through simulation-driven process evaluation

J. Stoldt [1], D. Neumann [1], T. Langer [1], M. Putz [1], A. Schlegel [1]

[1] Fraunhofer Institute for Machine Tools and Forming Technology, Chemnitz, Germany

Abstract

Continuous improvement of the production efficiency is one of many goals a company has for attaining a sustainable market position. When considering traditional objectives, benchmarks are used to compare numerous improvements concerning required inputs and created outputs. Adopting this approach for increasing the energy efficiency of individual manufacturing steps is difficult as their comparability is usually low. However, motivated by the need for competitiveness, regulatory mandates, and a desire for proactive green behaviour, companies seek for sustainable measures to make their manufacturing operations environmentally benign and thus require means for the ecologic assessment of their production processes. This paper presents a novel approach to benchmarking and process evolution, which minds both traditional economic and energy related key performance indicators (KPI). For this purpose, a procedure model making use of an enhanced material flow simulation system has been developed to evaluate and scrutinize the energy efficiency in production processes.

Keywords:

Benchmarking; Energy efficiency; Process evolution; Simulation

1 INTRODUCTION

Companies need to be innovative throughout their operation, if they want to sustain or improve their market position. This includes, for instance, the development of products, the advancement of business processes, or the optimisation of production operations. Hence, it is a management task to promote and monitor innovative developments. One common tool to foster business improvements is benchmarking. Recent surveys rank it as the most popular management instrument [1]. Its success is based on the ability to increase a company's "performance by identifying and applying best documented practices," using key performance indicators (KPI) to evaluate the efficacy of organisations [1]. The comparison with other companies and the afore-mentioned focus on "best practices" are the reasons for its great improvement potential [2]. While numerous KPI exist for specific purposes, it is difficult to compare the ecological efficiency of different production processes and technologies.

However, in light of expected supply shortages of raw materials, as well as fossil energy carriers (i.e. oil, coal, etc.), and with respect to the effects of an increased usage of natural energy sources (i.e. wind, sun, tides, etc.), companies have to mind their resource usage behaviour. This is intensified by customer demands, regulatory mandates, the pursuit of competitive economic advantages, and the desire for proactive green behaviour, which act as motivators for environmentally benign manufacturing [3]. In conclusion, there is a strong need for management instruments that help to foster the energy efficiency of complex production processes. If they are expected to gain broad acceptance they need to be truly generic, thus allowing for the evaluation and comparison of various production technologies, as well as combinations thereof employed in any desired factory.

While benchmarking is already a state of the art tool for improving the resource efficiency of processes [4], this paper introduces a new approach which allows for the comparison of different production technologies. Unlike other work in this field of research (e.g. [5-7]) it is focussed on the evaluation of manufacturing processes on an arbitrary level of detail. Following the "performance per watts" KPI in information technology (IT) [8], this novel methodology aims to evaluate the performance of production facilities and equipment. In order to support the implementation of energy efficiency increasing measures, it will make extensive use of energy-enriched material flow simulation. Hereby, it will be possible to effectively predict the impact of planned changes on the energy usage and the overall system productivity. Using simulation software for benchmarking purposes is not unique to the approach presented in this paper (e.g. [9]), however, the ability to be able to conjointly regard traditional (economic) and energy-related (ecological) KPI in a single simulation model is. The work presented in this paper is to be understood as a proof of concept for the developed methodology. Hence, all of the examples demonstrate the basic capability of this novel approach but do not use data acquired in a real production environment.

Hereafter, the general methodology and the newly developed (energy-related) process efficiency coefficient will be elaborated. Section 3 discusses how measures increasing energy efficiency can be devised and implemented utilising this new approach to benchmarking. The following section 4 describes how the methodology can be implemented into a simulation model and how the necessary data can be obtained from existing IT systems in the production environment. A brief summary will then conclude this paper.

2 BENCHMARKING THE ENERGY EFFICIENCY OF PRODUCTION PROCESSES

Including ecological considerations into the benchmarking methodology requires changes to the basic methodology as

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

well as the definition of novel KPI. These are described in the following subsections.

2.1 General methodology

The continuous advancement of all business processes allows for the gradual improvement of the organisational performance. Further combining benchmarking with value chain management allows for even greater efficiency throughout the production system. If these conventional considerations are expanded to include aspects of energy efficiency, the potential to realise sustainable improvements increases significantly.

Traditional benchmarking has been the subject of numerous publications; accordingly, there are varying suggestions for its conduct. Andersen describes the procedure utilising a wheel metaphor, emphasising the iterative character of the method [10]. According to this author, the following five steps should be performed:

1. Plan: Critical success factors, select a process for benchmarking, document the process, and develop performance measures.
2. Search: Find benchmarking partners.
3. Observe: Understand and document the partners' process, both performance and practice.
4. Analyze: Identify gaps in performance and find the root causes for the performance gaps.
5. Adapt: Choose "best practice", adapt to the company's conditions, and implement changes.

In contrast to a traditional benchmarking process, the new approach presented in this paper aims to allow for the immediate comparison of technological process regarding energy efficiency. For this purpose, a number of adjustments have to be made, resulting in the following seven steps:

1. Definition of traditional and energy-related KPI, level of abstraction, and processes/ equipment to be analysed.
2. Measurement of relevant data and description of the processes with their respective key production features.
3. Analysis of relevant data, evaluation of KPI, and ranking of individual processes.
4. Analysis of result and feature varieties as well as identification of related improvement potentials.
5. Identification and adaption of "best practices".
6. Simulation-based assessment of planned process alterations.
7. Implementation of effective measures.

The measurement of data in step two can be made either in the actual production environment or in a simulation model thereof. This allows for prospectively benchmarking production systems which are still in a design phase in order to determine an optimal solution, from both an ecologic and an economic point of view.

The explicit definition of the simulation of planned process alterations as part of the methodology aims to minimise the risk of failure through unintended side effects of their implementation. These are more prone to appear due to the increased complexity of the considerations caused by simultaneously aiming for both an economic and an ecologic optimum.

How this general methodology for benchmarking can benefit from value chain management will be detailed in the next subsection with respect to a process efficiency coefficient. The latter is the core KPI for the afore-described approach.

2.2 Quantifying (energetic) process efficiency

Individual production processes should be assessed just like companies are. The most relevant figures for any operation are profit (*P*), revenues (*R*) and costs (*C*). These have the relationship:

$$P = R - C \tag{1}$$

Revenues are generated by selling the actual products which is usually not possible for individual steps of the production process. Accordingly, there is a need to determine a replacement for revenues. Considering that any production step should aim to add value to the final product, added value (*AV*) is suitable. Consequently, the target figure can no longer be called profit, as no actual profit has been made at any point in the manufacturing process. Hence, the pseudo target figure rectified added value (*RAV*) replaces profit:

$$RAV = AV - C \tag{2}$$

A process efficiency coefficient (*EC*) can be deduced from this formula, keeping in mind that greater efficiency equals a greater rectified added value:

$$EC = \frac{AV}{C} \tag{3}$$

It is apparent that by definition, the costs may not be zero, which is, however, unlikely in a real production environment. This definition includes costs as a single factor although there are various factors within the overall production process which induce costs, such as labour, write-offs, raw materials, consumables, maintenance, energy, peripherals (e.g. lighting, or climate control), and so forth. While some may be quantified for individual process steps, many may not be. A mathematical expression of the relation of the costs and these cost factors (CF_i with $i=1,\ldots,I$ as the respective factor) – which are usually determined by means of a measurable consumption ($Cons_i$) and a cost per unit rate (CPU_i) – is:

$$C = \sum_i^I CF_i = \sum_i^I Cons_i \bullet CPU_i \tag{4}$$

In order to work around the tedious effort necessary to determine the overall costs – if even possible for individual production steps – the approach presented in this paper does not aim to use a single KPI (e.g. overall efficiency coefficient) but rather a flexible array of similar KPI. For this purpose, costs are replaced with the actual quantifiable consumption. Accordingly, the process efficiency coefficient (EC_i) is redefined to be unique for each cost factor:

$$EC_i = \frac{AV}{Cons_i} \tag{5}$$

A more specific version of this coefficient is the energy efficiency coefficient (eEC_i), which replaces the abstract concept of consumption with the actual consumption of energy or energy carriers ($eCons_i$), such as electricity, compressed air, or cooling water. It is defined as follows:

$$eEC_i = \frac{AV}{eCons_i} \tag{6}$$

A similar KPI has also been suggested by Reinhart et al. [11]. In contrast to these authors, it should be noted that the energy efficiency coefficients are expected to be applied to various carriers and alongside other traditional performance KPI (e.g. added value per hour of labour). The individual results should then be interpreted together in order to assess the process' overall efficiency. Which factors should be considered has to be determined in step one of the benchmarking methodology (see previous subsection).

Acquiring data for the consumption of any cost factor is dependent on the characteristics of these. The added value should always be determined by means of value chain management methods, e.g. value stream design.

3 MEASURES FOR INCREASING ENERGY EFFICIENCY

The presented benchmarking procedure allows for the comparison of different processes of a single company or of different companies. These processes can be planned and optimised taking differences between themselves and other more efficient implementations of the same or a different technology into consideration. In order to improve the results, a systemised approach should be followed. Figure 1 depicts a more in-depth overview of the tasks which are included in steps four and five of the benchmarking methodology presented in section 2.1.

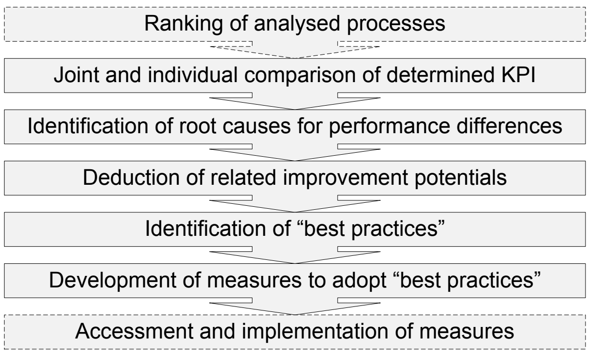


Figure 1: Process steps for deduction of measures.

Accordingly, the first step is to compare the determined KPI of the ranked processes with each other. In order to assess the differences thoroughly and to identify correlations, the various KPI should be compared individually and conjointly. Having determined the major performance differences, their individual root causes should be investigated. These are very much dependent on the compared processes and their technologies. Hence, they provide input on the question how the process efficiency can be increased. The deduction of this particular piece of information, i.e. improvement potentials related to the results of the comparison, is part of the following step. Once the potentials to be tapped have been decided, "best practices" should be identified. While the compared processes may already be labelled the "best practice", they do not necessarily have to be. Consequently, a search for the best available solution should be made. Based on the results of the previous steps, measures aimed at the adaption of the "best practice" have to be developed.

For this purpose, the two dimensions of the presented (energy) efficiency coefficient should be considered. Utilising these, all assessed processes can be visualised on a plane, as depicted in figure 2. It should be noted that this portrayal is unique to any specified KPI (EC_i / eEC_i). The actual efficiency of each process is determined by the slope of the line connecting the point of the process and the point of origin.

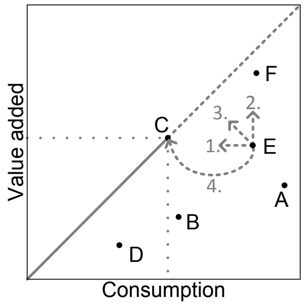


Figure 2: Visualisation of efficiency improvement approaches.

In order to devise measures which improve the efficiency of a production process, four fundamental approaches exist (see figure 2), which should be combined with the knowledge of the identified "best practices". These are explained hereafter:

1. Decreasing consumption: Basically two ways to reduce the consumption of energy exist. On the one hand, equipment losses can be minimised by utilising more efficient components and higher grade consumables. On the other hand, avoidable wasteful behaviour (see [11]), such as prolonged equipment idle time, can be reduced. Decreasing the consumption of other cost factors is also closely related to the elimination of waste, as propagated by Lean Management [12] and the Toyota Production System [13].
2. Increasing added value: The basic idea of this approach is to increase the added value without changing the consumption of cost factors. This can be achieved by intensifying the labour, for instance, so that more work is completed in the same time.
3. Combination of 1. and 2.: While most devisable measures are likely to be a combination of 1. and 2., there are some situations when considerable effort is put into decreasing consumption and increasing added value. The integration of entire process chains (e.g. [14]) is a prime example for this, where functionality of multiple machines is integrated into a single one. Thereby, the added value created by a single machine is increased and redundant components, such as multiple controllers, can be removed.
4. Process substitution: Instead of adjusting, advancing, and improving existing processes to improve their efficiency, they may also be substituted with entirely new processes. This approach is especially feasible, if newly developed technologies promise a significantly higher efficiency despite higher costs for their implementation.

During the development of measures aimed at the adoption of "best practices", the desired and anticipated effects on all regarded KPI should be considered. As this can be quite complicated, especially when using a large array of KPI, the basic methodology suggests simulations prior to the measure implementation. This will be discussed in more detail in the following section.

4 SIMULATION IN THE BENCHMARKING PROCESS

The importance of simulation within the benchmarking methodology has already been discussed in the previous sections. More precisely, it can be used to generate initial input for the generation of KPI and to validate the effectiveness of devised measures prior to their implementations. The fundamental approach is hereafter exemplified by means of a use-case.

4.1 Implementation of the methodology

In order to move towards a holistic benchmarking which allows for comparing various processes, a wide variety of data needs to be assessed. This includes, amongst others, the consumption of energy, energy carriers, and raw material, as well as the required amount of labour, the size of material stocks, and equipment availability data. Regarding these conjointly becomes increasingly difficult, if larger production systems and more stochastic events (e.g. random equipment break downs) are considered. Discrete event simulation software solutions are ideal tools to reduce the necessary effort for such investigation. Hence, the hereafter presented approach makes use of the established Tecnomatix Plant Simulation software to determine input for the evaluation of specific KPI.

For this purpose, a model of an exemplary production system has been created, which represents the manual assembly and finish part of a car body production. Versions of produced cars with both three and five doors are regarded during simulation. The production system itself consists of a main line with five interlinked and clocked work stations (WS), as well as eight subsystems, which supply – in teams of two – parts to the earlier four work stations. These four assemble the doors of the five-door version, the bonnet and tailgate, the doors of the three-door version, and the wings to the otherwise complete car bodies. Afterwards, employees in the fifth work station, a light tunnel, check for any imperfections which would diminish the quality of the final product. The individual subsystems, which supply the afore-mentioned parts to the main line, are made up of between one and five robot work groups (WG). A schematic of this system is depicted in the lower half of figure 3.

All these work groups and work stations have been modelled utilising the VDA Automotive Toolkit [15]. As Plant Simulation does offer no functionality to regard the energy consumption of the production equipment during run time, an own solution, called eniBRIC, has been developed [16]. These eniBRIC modules enrich existing material flow objects – in this case from the VDA Automotive Toolkit –, providing a way to estimate the consumption of energy, energy carriers, and other process prerequisites. In particular, electricity, compressed air, cooling water, lighting, smoulder suction, laser light, and ventilation, as well as their respective suppliers are regarded.

Once the simulation model had been created and enabled to regard energy consumption, data for its parameters had to be selected and entered. As this is a very important part of any simulation study, the following section 4.2 will cover it in more detail. Afterwards, preparations for the benchmarking process have been made. This entailed writing routines to collect all necessary input data for the KPI evaluation, paying close attention to selected measuring points. With respect to the definition of the EC and the eEC (formulas (5) and (6)), a consumption for any regarded cost driver had to be identified and subsequently measured during simulation. Furthermore, a data base of the value added by any simulated process needed to be created and stored for later references. These sets of data are combined during or after individual simulation runs to evaluate the individually examined KPI, i.e. EC and eEC, as can be seen in the upper half of figure 3.

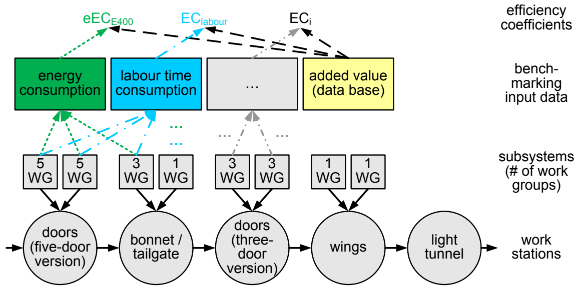


Figure 3: Schematic of regarded production system and data relationships within the simulation model.

The simulation model has been prepared accordingly, aiming to benchmark the processes (i.e. work groups and work stations) with respect to their consumption of electricity at 400 V (eEC$_{E400}$) and labour time (EC$_{labour}$). In order to determine appropriate measuring points, preliminary considerations regarding the effects that should be included in the investigation have been made. For this purpose, a process chain of three non-elastically interlinked processes with identical cycle time is regarded (see figure 4). If a failure (red) occurs during operation (green) in the second process (P2), the time until it completes the current part and accepts a new part increases. Consequently, the prior process (P1) will be blocked (blue), as it can not commence work on a new part unless the previous one has left. Similarly, the following process (P3) has to wait (yellow) until P2 has finished part 3. Considering these interactions, it is clear that the measuring points can be at the beginning and the end of the processing, excluding foreign influences, or always at the beginning of the processing. As these interactions should be regarded for the following evaluation, the latter approach has been chosen for this investigation. Hence, the consumption of energy and (labour) time between two entering parts is logged for each process during simulation runs. The KPI are then evaluated using the average consumption.

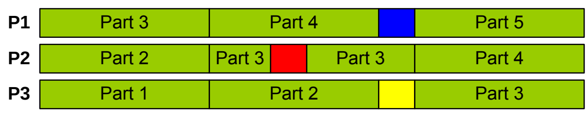


Figure 4: Consequences of errors in a process chain.

An exemplary application of the simulation model in a minor benchmarking study shall illustrate how the simulation approach benefits the general methodology. Having already defined KPI and the processes to be analysed, the status quo is investigated through simulation, as suggested for step two of the methodology (see section 2.1). Since the data is automatically used to evaluate the KPI, the results can be analysed immediately. These show clearly that the main line acts as the bottleneck of the entire production system, causing frequent blockages of the supplying subsystems. Skipping in-depth elaboration on best practices to avoid these blockages, a measure is devised to reduce them. In particular, the main line cycle time is reduced by 2 seconds, which resembles approach two identified in section 3. Taking into consideration that increasing the work intensity of manual labour – as present on the main line – can be very hard to achieve, a preliminary investigation should be made to estimate the potential. Hence, the simulation model is altered accordingly and used again in step six of the methodology, proving the general effectiveness of the devised measure. Table 1 depicts some exemplary data collected as part of the simulation effort in this benchmarking study. For this purpose, the added value of all processes has been set to 100 monetary units. Both experiments (before and after optimisation) had a duration of 45 days and have been repeated 50 times in order to reach statistical certainty despite randomly occurring events (e.g. break downs).

Table 1: Exemplary results of the benchmarking study.

Process name		eEC_{E400}		EC_{labour}	
		before	after	before	after
WS_1	mean	1,61	1,66	0,88	0,91
	Δ	+0,05		+0,03	
WG_{bonnet}	mean	0,80	0,83	1,46	1,50
	Δ	+0,02		+0,04	
WG_{wings1}	mean	1,68	1,73	1,46	1,50
	Δ	+0,05		+0,04	

4.2 Data acquisition in a corporate environment

The easy and flexible acquisition of realistic and complete data for the parameterisation of the presented simulation model is of great importance. This is benefitted by the substantial and still increasing support of production systems by IT-based (data) management solutions. In order to foster the general quality of the data used for the simulation, it is an asset to extract the model parameters from these existing IT systems. Figure 5 gives an exemplary overview on possible data sources, the information they can provide, and specific data sets.

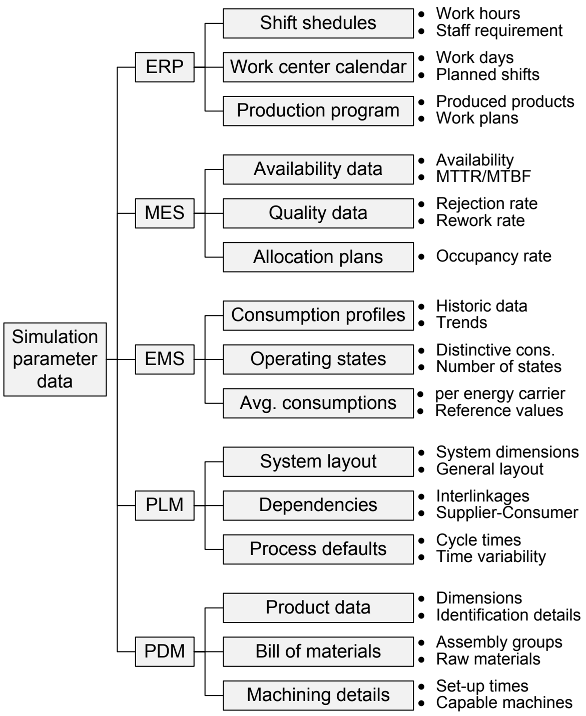


Figure 5: Sources for simulation parameter data.

Hereafter, the focus lies on the following sets of information:

- production program;
- product quality;
- consumption of energy and energy carriers;
- common operating states of equipment;
- equipment availability;
- production system defaults (e.g. cycle time).

Enterprise Resource Planning (ERP) solutions are state of the art in most companies. Through direct access to their underlying data base or using specific software-based application programming interfaces (API) it is possible to gather and to extract information regarding the production program of the system under consideration. This is important to ascertain which products are produced in which quantity, for instance. Furthermore, work plans for individual products can be determined, although these will usually have to be formalised to be usable in a simulation.

Process- and quality related data is usually managed by specific modules of Manufacturing Execution Systems (MES) [17]. These pieces of information are frequently complemented by data on the consumption of energy and other process resources, which in turn may be acquired by Energy Management Systems (EMS) as process information relating to either individual products or employed equipment. For the approach to simulation including energy-related considerations introduced in the previous section, yet not exclusively for this one, it is important to determine certain operating states and their respective energy and energy carrier consumption. Such information can be derived automatically or semi-automatically from recorded consumption profiles, depending on the complexity of the profiles and the available software.

If the simulated equipment and processes are to behave realistically, detailed knowledge of their availability and break down behaviour is required. Nowadays, corresponding data is predominantly gathered and analysed during production and stored in specialised availability management systems. Based on the concept of multivalent data usage various approaches to reuse already acquired data for other purposes than their originally intended one exist. The method for the product data based productivity assessment is an example in this context [18,19]. It aims to deduct information on the effectiveness of equipment in interlinked production systems from product data available in traceability solutions.

Additionally, information regarding production process defaults – which often depend on the manufactured product types – is required to parameterise simulation models. This includes cycle times, the variability thereof etc. and is usually stored in Product Lifecycle Management (PLM) solutions.

Product Data Management (PDM) software is also state of the art in most companies and holds most product related data, depending on the company specific implementation. All these systems store the data independently, which makes the data acquisition for simulation studies difficult. Hence, Fraunhofer IWU searches for and develops new approaches to creating links between all the individual data sets [20], in order to drastically reduce the necessary effort.

5 SUMMARY

In order to increase the energy efficiency of production systems a novel approach to benchmarking has been presented. Its basic methodology along with the efficiency and energy efficiency coefficient allow for the assessment of the performance of individual manufacturing processes on an arbitrary level. This information can be used to identify improvement potentials and derive measures to exploit the latter, effectively improving both the ecological and economic performance of the regarded production system. Furthermore, it has been shown how the developed benchmarking methodology can be complemented with simulation studies and where necessary input data for this purpose may be acquired.

At this point, the (energy) efficiency coefficient can only be utilised to assess the performance of value adding processes while many indirect processes, such as in-plant logistics, can not be considered. Future research will have to focus on KPI that close this gap.

6 ACKNOWLEDGMENTS

The presented work summarizes outcomes of the research projects InnoCaT® and eniPROD®. The pre-competetive joint research project "Innovation Alliance Green Car Body Technologies" is funded by the "Bundesministerium für Bildung und Forschung (BMBF)" (funding mark 02PO2700 ff) and supervised by "Projektträger Karlsruhe (PTKA)". The authors are responsible for the content of the publication. The Cluster of Excellence "Energy-Efficient Product and Process Innovation in Production Engineering" (eniPROD®) is funded by the European Union (European Regional Development Fund) and the Free State of Saxony.

7 REFERENCES

[1] Bogetoft, P., 2012, Performance Benchamrking, Springer-Verlag, New York.

[2] Camp, R. C., 1989, Benchmarking. The search for industry best practices that lead to superior performance, Quality Press; Quality Resources, Milwaukee, Wis, White Plains, N.Y.

[3] Gutowski, T.; Murphy, C.; Allen, D.; Bauer, D.; Bras, B.; Piwonka, T.; Scheng, P.; Sutherland, J.; Thurston, D.; Wolf, E., 2005: Environmentally benign manufacturing: Observations from Japan, Europe and the United States, in: Journal of Cleaner Production, Vol. 13, No. 1, pp. 1-17.

[4] Kristof, Kora; Türk, Volker, 2006, Ressourceneffizienz-steigerungen durch unternehmensübergreifende Instrumente. Status-Quo Analyse, Kritik, Politik-empfehlungen, Wuppertal.

[5] Stich, V.; Brandenburg, U.; Kropp, S., 2012, Benchmarking Concept for Energy Efficiency in the Manufacturing Industry – A Holistic Energy Efficiency Model, in: Advances in Production Management Systems. Value Networks: Innovation, Technologies, and Management, pp. 390-395.

[6] Mertins, K.; Kohl, H.; Riebartsch, O., 2011, Sustainable Key-Figure Benchmarking for Small and Medium Sized Enterprises, in: Proceedings of the 9th Global Conference on Sustainable Manufacturing, St. Petersburg, pp. 309-314.

[7] Mertins, K.; Kohl, H.; Riebartsch, O., 2012, Benchmarking: The ideal Management Tool to exploit the "Triple Bottom Line of Sustainability" for long-term Success in Manufacturing Industries, in: Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, pp. 594-601.

[8] Huppler, K. R., 2013, Performance Per Watt - Benchmarking Ways to Get More for Less, in: Proceedings of the 4th TPC Technology Conference, Istanbul, pp. 60-74.

[9] Tereci, A.; Ozkan, S. T. E.; Eicker, U., 2013, Energy benchmarking for residential buildings, in: Energy and Buildings, Vol. 60, pp. 92-99.

[10] Andersen, B., 1998, Industrial Benchmarking for Competitive Advantage, in: Proceedings of the ESPRIT-COPERNICUS Symposium on Distributed Enterprise, Intelligent Automation and Industrial Benchmarking - Putting Information and Communication Technologies into Practice, Wrocław.

[11] Reinhart, G.; Karl, F.; Krebs, P.; Reinhardt, S., 2010, Energiewertstrom – Eine Methode zur ganzheitlichen Erhöhung der Energieproduktivität, in: Zeitschrift für wirtschaftlichen Fabrikbetrieb – ZWF, 2010/10, pp. 870-875.

[12] Reitz, A., 2008, LEAN TPM – in 12 Schritten zum schlanken Managementsystem, MI Wirtschaftsbuch, München.

[13] Ohno, T., 1988, Toyota Production System: Beyond Large-Scale Production, Productivity Press, New York.

[14] Sterzing, A.; Neugebauer, R.; Drossel, W.-G., 2013, Metal Forming – Challenges from a Green Perspective, in: Proceedings of the International Conference on Competitive Manufacturing, Stellenbosch, pp. 19-24.

[15] Mayer, G.; Pöge, C., 2010: The Road to Standardization: From the Idea to Realization of the VDA Automotive Toolkit, in: Zülch, G. (Ed.): Integration Aspects of Simulation: Equipment, Organization and Personnel, KIT Scientific Publishing, Karlsruhe, pp. 29-36.

[16] Stoldt, J.; Schlegel, A.; Franz, E.; Langer, T.; Putz, M., 2013, Generic energy-enhancement module for consumption analysis of manufacturing processes in discrete event simulation, in: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore, pp.162-170.

[17] VDI, 2011, VDI-Richtlinie 5600: Fertigungsmanagement-systeme (Manufacturing Execution Systems – MES), Beuth Verlag, Berlin.

[18] Neugebauer, R.; Kreppenhofer, D.; Langer, T., 2010, Determination of the overall equipment effectiveness for assembly systems on the base of product data, in: 43rd CIRP International Conference on Manufacturing Systems, Vienna, pp. 991-999.

[19] Putz, M., 2012, Determination of extended availability and productivity statements for assembly systems using existing data base, in: Annals of the CIRP, Vol. 61, No. 1, pp. 17-20.

[20] Putz, M.; Schreiber, A.; Firlej, A.; Langer, T., 2013, Linked Factory – Datenintegration zur mobilen Informationsbereitstellung in der Produktion, in: Proceedings of the 19th Industriearbeitskreis “Kooperation im Anlagenbau”, Magdeburg.

GCSM 11th Global Conference on Sustainable Manufacturing
2013 23rd - 25th September Berlin - Germany

15.5 Life cycle evaluation of factories: Approach, tool and case study

T. Heinemann[1], S. Thiede[1], K. Müller[2], B. Berning[1], J. Linzbach[3], C. Herrmann[1]

[1]Sustainable Manufacturing and Life Cycle Engineering Research Group, Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Germany

[2] Siemens AG - Corporate Technology, Germany

[3] Festo AG & Co. KG, Germany

Abstract

During the planning phase of the build up or overhaul of factories a large share of the life-cycle-spanning impact of such production facilities is determined. This fact creates a big challenge as a factory is a very complex system and there are various uncertainties regarding the mode of operation and unexpected events that can affect the costs and ecological as well as social impact of a factory during its entire life cycle. Furthermore the life cycle of a factory often even exceeds the time horizon of strategic management decisions. So do also the ecological burdens that are created by the factory. Against this background this paper presents an integrated life cycle evaluation approach for a streamlined economical, ecological and social life cycle assessment of factory systems. The approach also gets transformed into a tool which is used in order to evaluate case studies on machine and factory level.

Keywords:

Factory Planning; Life Cycle Evaluation; Strategic Decision Support; Total Cost of Ownership

1 INTRODUCTION

Through various drivers increasing the sustainability of factories is a major concern in manufacturing companies nowadays [1]. According to the definitions like given from the Brundtland commission this involves three dimensions: economic, ecological and social sustainability [2]. Whereas traditionally the economic perspective was and still is the major driver, companies strive towards a more balanced set of objectives. However, solving this challenge is a complex task and might cause conflicts of goals. Even more, it is important to take the full life cycle of products and processes into account in order to avoid local optimization of one phase with possible problem shifting to other life cycle phases [3]. For assessing the economic, ecological and social performance a variety of specific methods and tools (based on the basic paradigms of Life Cycle Costs/LCC, Life Cycle Assessment/LCA, Social Life Cycle Assessment/SLCA) were developed over the years. They require significant amounts of data and are rarely used in synergetic combination (e.g. usage of same data input). Even more, due to the complexity of the system those approaches are typically not used for factories as a whole with all its relevant elements.

Against this background, this paper provides a framework for the life cycle evaluation of factories from economic, ecological and social perspective. Even more, this framework was already embodied into a comprehensive software tool which guides the user through the life cycle oriented evaluation process. Besides presenting the methodological background, the paper demonstrates applicability and benefits through a case study.

2 THEORETICAL BACKGROUND

2.1 Holistic system comprehension and Factory Elements

The first step of an analysis and evaluation process is naturally the clear definition of the considered system and its boundaries. Within this paper, the factory system as a whole is the subject of investigation. It consists of three main subsystems which shall all be taken into account and analysed in an integrated manner (Figure 1) [3] [4]:

- production equipment: processes/machines which form value adding process chains
- technical building services: responsible for providing production conditions (in terms of moisture, temperature and purity) and energy as well as media
- building shell: physical boundary of the factory system and to the outside which includes influences of the local climate

Those subsystems dynamically interact over time and therefore have to be considered as a meta-control system. However, their individual design and control involves diverse disciplines like civil, production, energy or electrical engineering which impedes a synergetic planning of the factory system. Thus, methods and tools to overcome those interdisciplinary challenges are a proper way towards more sustainable solutions.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

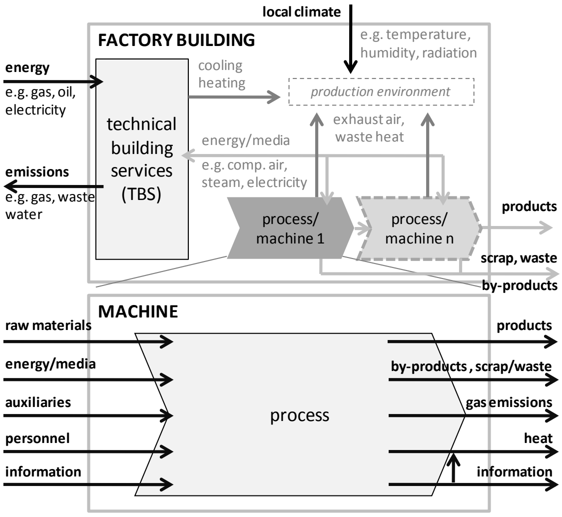


Figure 1: Holistic understanding of factory system.

2.2 Life Cycle Costing / Total Cost of Ownership

Life cycle costing (LCC, economic life cycle evaluation) is an extension of traditional acquisition cost oriented concepts. It considers all economically relevant monetary flows over the whole life cycle of products [3]. Therewith, LCC allows analysing trade-offs between different life cycle phases and, thus, supports to derive optimized solutions from a comprehensive perspective. Within the last years, diverse general frameworks for life cycle costing in form of standards, norms or guidelines have been developed (e.g. VDMA 34160, VDI 2884, DIN EN 60300). They differ in terms of e.g. involved life cycle phases, definition of cost portions, stakeholder perspectives, rules for calculation (e.g. consideration of discounting) or transferability to different branches [5]. In this context, Total Cost of Ownership (TCO) is a selected perspective on life cycle costs. It focuses on the operator/user perspective of the considered object and all the costs that occur during the course of ownership. Examples are costs for acquisition, installation, training, energy, maintenance, planned or unplanned downtime and disposal (e.g. [6]). To ease application, manifold software based tools which also differ in terms of scope, field of application and general functionalities were developed over the years [7]. However, those solutions tend to be quite specific for selected applications (e.g. components, specific technical equipment) and are rather focusing on single object whereas less considering systems as a whole – i.e. tools for supporting LCC/TCO calculation for factory systems with all relevant subsystems cannot be found so far.

2.3 Life Cycle Assessment

Life cycle assessment focuses mainly on environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition through production, use, end-of life treatment, recycling and final disposal [8].

Manufacturing processes are considered as part of a product evaluation to achieve optimal overall sustainability performance of a product. Several researchers have also investigated the environmental impact of specific manufacturing processes to support the development of environmental conscious processes and the decision on process alternatives to be considered for the manufacturing of a product. There are numbers of publications on product and process metrics to be evaluated [9].

On the factory level there is a common sense on reporting environmental, economic and social performance indicators under the framework of the Global Reporting Initiative (GRI) [10]. In this context of reporting, the efficient operation of a factory and its processes is focused and measurements and investigations on machine, workstation or line level take place partly.

However, understanding a factory as a changing system with its own life cycle enabling a sustainable business has not been investigated sufficiently neither has the life cycle assessment been integrated into factory planning processes.

During the factory planning phase there are a number of areas to be investigated and developed and the methodology of the life cycle assessment could deliver a comprehensive decision support e.g. for

- Location planning,
- Rough and revised layout optimization,
- Material flow planning,
- Dimensioning and selection of technologies,
- Assessment of technical, economic variations and benefit analysis, etc.

3 LIFE CYCLE EVALUATION APPROACH AND ARCHITECTURE

3.1 Scope and requirements

There are manifold challenges to deal with as a factory is a very complex system and there are various uncertainties regarding the mode of operation and unexpected events that can affect the cost and ecological as well as social impact of a factory during its entire life cycle. Furthermore the life cycle of a factory often even exceeds the time horizon of strategic management decisions. So do also the ecological burdens that are created by the factory. Due to this fact an integrated life cycle evaluation approach needs to be developed that combines detailed financial controlling schemes and ecological as well as social impact assessment tools for the life cycle of factories in order to support sustainable decisions for future eco-factories. Through this approach the planning team for new factories or factories that need to be overhauled shall be enabled to make estimations about the total cost of ownership, the ecological impact and social issues that result from the installation and operation of a factory. After applying the life cycle evaluation approach there shall be transparency over the structure and drivers of the cost and ecological as well as social impacts of the factory and the comparison of different configuration options is possible in order to identify the most sustainable factory system.

The life cycle evaluation approach is part of the total factory planning process. Within this process it is applied in an early stage as soon as first drafts of the new factory system and its sub-elements are defined. The life cycle evaluation approach is used in order to evaluate and preselect first planning scenarios which will be developed further afterwards. During the later stages of the factory planning process the life cycle evaluation approach can iteratively be used in order to assess the economic, ecological and social impact of more detailed drafts of the planned factory even regarding the chosen components of single factory elements.

Therefore this paper focuses mainly on the system elements of the focused factory such as the building shell, the technical building services and the production equipment itself. Given these boundary conditions the described life cycle evaluation approach is used when the decision to build a new or overhaul an existing factory at a given location has been taken and does not cover the location planning and the interaction between workstation, production line, layout, and schedule in detail.

The following three main requirements have been considered developing the life cycle assessment approach of factories:

1. The life cycle evaluation of factories shall enable the assessment of different hierarchical layers in the factory system and therefore also enable the processing of data with diverse levels of detail:

   System level: A comprehensive overall view considering all system elements of the factory: building shell, technical building services and production equipment on relevant ecological, economic and social effects to figure out main drivers and to prioritize system elements to take care of and reduce environmental and social impacts as well as total cost of ownership before implementation.

   Equipment level: A detailed comparison of alternative technologies and technical equipments, workstations, machines to figure out the best solution to implement from an overall life cycle perspective.

2. The life cycle evaluation of factory planning shall also allow different time-resolutions to investigate a one-year-period as functional unit of the factory as well as the time horizon of the overall system. So the input data regarding physical flows and monetary as well as ecological evaluation factors needs to be aggregated to datasets one a yearly basis.
3. Depending on the stage of the factory planning process the approach shall allow different levels of accuracy of the input data (e.g. estimations, default values, measurements). In early phases only basic information is available and the remaining required input data base on default data or preconfigured models. As the factory planning process precedes more and more information is available and the life cycle model of the factory can be detailed and enhanced.

3.2 Architecture of the Life Cycle Evaluation approach

The Life Cycle Evaluation approach requires a set of general settings data with predefined values, a data entry section to model the different factory elements and a calculation section to report the environmental indicators, input and output flows as well as total cost of ownership in a table and diagram format. All calculations and evaluations within the life cycle evaluation approach are based on cumulated physical input and output flows (see Figure 2) over each evaluation period within the life cycle (such as life cycle inventories) of the focused system, which can be a factory system or selected sub-systems. These flows are based on energy, media and material consumption profiles which are taken from data sheets of the single elements of the factory system as well as from (externally simulated) forecasts of the operation modes of the factory. It is important to state that during the use phase of the factory and its system elements also the utilization, shift models, downtimes, etc. are used in order to calculate (and simulate) real consumption profiles as basis for the overall physical input and output flows. Every factory element that shall be modelled gets described as a set of parameters with physical units first before any evaluation can start. All (economical and ecological) evaluation is done afterwards by transforming the physical flow data into financial or ecological impact information by multiplying it with cost/benefit-factors as well as ecological impact factors (such as CO_2eq.) which are partly predefined in the tool but also can be adapted freely according to the demands of the tool's customer. The resulting cost/benefit schedules are enriched with interest rates and depreciation allowances in order to calculate the total cost of ownership of the factory system. Social issues within the Life Cycle Evaluation Tool are addressed regarding individual indicators which correspond with the guidelines of the GRI such as the amount of non-precarious jobs that are created through the factory system and the needed level of qualification for these jobs. Following this logic the approach is coherent to the steps of a Life Cycle Assessment. The definition of the general settings of the evaluation project constitutes the goal and scope of the evaluation, the calculation of physical flows creates a life cycle inventory analysis (LCI) and the transformation to economical and ecological impact categories builds up a life cycle impact assessment (LCIA), which can be interpreted afterwards. [8]

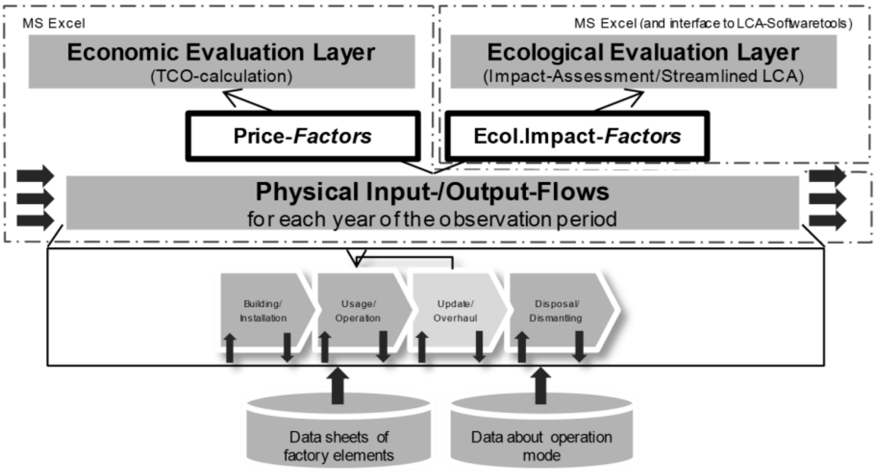


Figure 2: Architecture of the Life Cycle Evaluation Approach.

3.3 Data sources and tool interaction

Although the developed approach (and the derived tool) can be used as a standalone solution it can also be integrated into existing other approaches in two directions (see Figure 3):

1. Linking existing life cycle assessment data into the factory model,
2. Using results from the factory model for an in-depth and comprehensive environmental assessment.

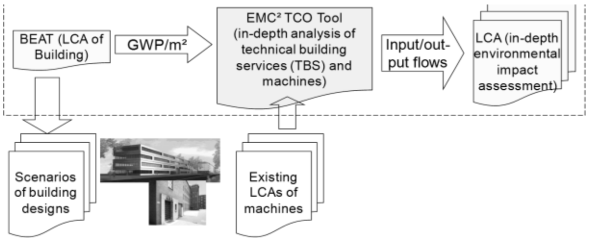


Figure 3: Data processing between tools.

As companies perform more and more life cycle assessments of their products there is a great opportunity to use existing assessments on equipment or building material in the factory model. Equipment suppliers might be requested to provide life cycle assessment data of their machines offered which can be integrated into the tool. The tool provides a number of existing equipments or building types which the user can select and combine to the model of the observed factory and/or compare different factory configuration options.

If there are no life cycle assessment results available the factory elements get characterized by the technical data sheet of these elements and impacts are calculated based on the general settings in the tool (e.g. emission factors, energy cost).

Due to the driving force of energy efficient factories the developed factory model focuses on the global warming potential as environmental impact category. However, a more detailed assessment of the factory's environmental impact can be done using existing life cycle assessment software and databases.

As a result of the factory model all input and output flows are reported. Without modelling the factory itself, the environmental impact of input and output flows can be characterized according to different impact categories or characterization methods of interest.

All major life cycle assessment tools offer import functionalities so it is quite easy to transfer the results of the Life Cycle Evaluation Approach to such tools by matching the input and output flow to existing processes in the life cycle assessment databases for further evaluation. In order to facilitate this data ex- and import the derived Life Cycle Evaluation Tool provides an extra table of all calculated physical flows that is prepared in order to be easily transferred to third-party LCA software tools.

3.4 Interaction with further tools of a green factory planning approach and output of the tool

Besides the interaction with other life cycle assessment tools the life cycle evaluation approach also supports green factory planning approaches (which are under development in the underlying EMC²-Fatory project) through the evaluation of planning scenarios regarding cost and ecological impacts [11] [12]. Therefore the results of the life cycle evaluation approach can be used in order to complement the results of single-machine-focused decision making tools which are used in order to support the individual selection of production equipment. Such decision making approaches can make use of the cost schedules and the ecological impact data which result from the life cycle evaluation tool. In case that the cost determining behaviour of some elements of the factory system is highly dynamic and cannot be estimated sufficiently, energy oriented factory system simulation approaches can give valuable input to the life cycle evaluation approach [13] [14]. Input from such a factory system simulation would be an exact prediction of the physical flows which are processed by the single factory elements such as energy and the yearly demand of auxiliary materials [15].

4 APPLICATION OF THE LIFE CYCLE EVALUATION TOOL

The Life Cycle Evaluation approach has been embodied into a software solution as a supporting tool to the factory planning process. The application of the tool follows a workflow which is depicted in Figure 4 and gets guided via an MS Excel™ based interface.

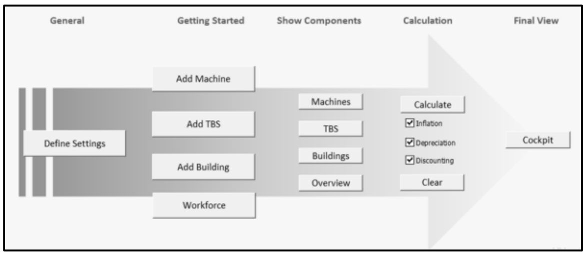


Figure 4: Workflow for the usage of the LCE Tool.

Before the modelling of a factory planning project the basic conditions of this project get defined in the **Define Settings** section. The definition of settings incorporates the definition of possible physical flow variables, their prices and the individual rate of price increase as well as their individual carbon footprint (CO2eq). Furthermore the settings section enables the user to modify the operating hours per year, the projection period (up to 30 years) for the factory planning project and the general design of the building shell (one floor vs. two floors, concrete walls with/without windows, etc.).

After the definition of the general settings, the user can model the single elements of the factory system such as machines, technical building services, the building shell and basic information about the employed workforce. The modelling of the technical elements is illustrated in Figure 5 using the example of the module **Add Machine**.

Figure 5: Machine modelling within the LCE Tool.

For each of the technical elements a set of general parameters needs to be set. These parameters are annual operating hours, required space, lifetime, maintenance interval (mean time between maintenance operations), maintenance expenses per average maintenance operation, initial investment costs, period of installation within the projection period, replacement after lifetime (yes/no) and the amount of identical machines.

Besides these general parameters the utilization (process, idle) as a percentage of the operating hours, the state dependent electrical power consumption and all relevant physical input and output flows need to be defined. The physical flows can be selected from the list of physical flows which has been defined in the settings section.

Having modelled the factory system and all its technical elements in the described way, it is possible to check and correct single variables and their values using the **Show Components** module. If all inserted data is correct the **Calculation** module can be run. This module accumulates all parameterized physical flows individually per evaluation period also regarding the states of the technical system elements. After the period based accumulation of physical flows has been done these flows get multiplied by the predefined economical prizes and ecological impact factors. The results of these calculation routines as well as further sustainability indicators that have been selected from the GRI [10] get visualized in the **Cockpit** module which generates printable reporting sheets that have the right format in order to support decision making meetings of the observed factory planning project. The comparative assessment of different factory configuration options or different machines and process technologies gets done through the individual modelling of these scenarios and the later comparison of the individual reporting sheets.

5 CASE STUDY

In order to show the application and potential of the Life Cycle Evaluation Tool a case study based on a generic SME case from metal processing sector has been conducted. For reasons of simplification, this case study only regards the physical flow of electrical energy in the use phase of the technical factory elements. The factory elements and general settings of this enterprise are depicted in Table 1:

Table 1: Selected model parameters for generic small enterprise in the metal processing sector.

Equipment	Machines	3x Milling, 3x Turning, 3x Grinding
	Technical Building Service	1x Air compressor
	Building shell	1 building, aerated concrete walls, 1 floor, no windows
Time	Annual operating hours	1650 h/a
	Projection period	30 years
Electricity	Electricity prize	0,15€/kWh
	Ecological impact	0,559 kg CO2eq/kWh
	Energy mix	European Energy Mix
Finance	Space costs	8 €/m²
	Interest rate	3%
	Inflation	1%
	Calculation options	Dynamic discounting and inflation rates enabled.
Assumptions	The environmental impact of the setup & disposal phase of the factory result only from the setup and disposal of the building shell. The ecological impact of the production equipment and technical building services results only from its usage, i.e. in this case only from its energy consumption. The data of the ecological impact of four generic types of building shells has been imported from a tool that creates LCAs for buildings [16].	

Together with the general settings and the detailed modelling of the technical factory elements the Life Cycle Evaluation Tool calculates the economical and ecological performance of the observed factory system. The following figures are taken directly from the reporting sheets of the Life Cycle Evaluation Tool. They illustrate some of the basic results, regarding economical, ecological and energy oriented issues.

Figure 6 shows the development of the TCO of the entire system as well as the cost development of the factory elements. One conclusion from this diagram is in year 15 the cost development of the production equipment exceeds the cost of the building shell although this has been by far the largest initial investment. Figure 6 also illustrates the cost fractions of the factory elements after the projection period of 30 years. Here the negligible impact of the technical building services can be observed. (This is only an effect of the specific case study and cannot be generalized, of course.)

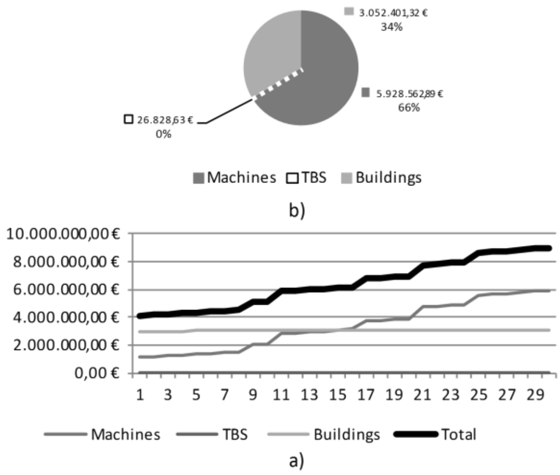


Figure 6: Cost development (a) and cost fractions (b) of the factory elements over 30 years.

Figure 7 shows the contribution of the life cycle phases to the ecological impact of the factory system. Under the given assumptions and restrictions the use phase of the factory is dominant. Within the use phase the usage of the production machinery determines most of the ecological burden compared to the technical building services.

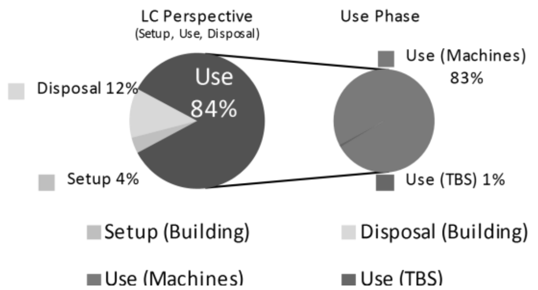


Figure 7: Contribution of life cycle phases to ecological impact of the factory system.

Figure 8 shows the state related electrical energy consumption of machines and technical building services during the factory use phase. By comparing both diagrams becomes obvious that in this case the energy consumption of the building services is relatively small compared to the production equipment. Looking at the production machines it stands out that the energy consumption during idle mode seems to be quite high. So the result visualization of the LCE Tool can even be used to identify fields of action for meaningful improvement measures of the factory planning project.

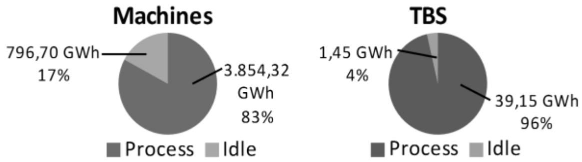


Figure 8: State related electrical energy consumption of machines and TBS during the factory use phase

6 CONCLUSION AND OUTLOOK

This paper presents a comprehensive Life Cycle Evaluation Approach and Tool for factory systems that is exemplarily applied to a case of a generic small enterprise from the metal processing industry. This LCE Tool incorporates externally generated data about ecological impacts and cost factors in a structured calculation routine. It enables the life cycle spanning evaluation of factory planning projects and generates indicators like e.g. total cost of ownership and ecological impact (global warming potential). It has to be stated that LCE Tool depends on a good data quality as an input and that the technical and logical meaningfulness of the evaluated scenarios or factory configuration options needs to be confirmed externally as this cannot be supported by the LCE Tool. Nevertheless the LCE Tool demonstrated its potential in order to facilitate the economical and ecological evaluation of different options in factory planning projects already at a very early stage of the factory planning process.

Future work will focus on more detailed case studies that represent real industry scenarios and innovative technological developments of the underlying EMC²-Factory project.

7 ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 285363. The funded project's title is Eco Manufactured Transportation Means from Clean and Competitive Factory" [EMC²-Factory]. For further information about the project visit the website www.emc2-factory.eu.

8 REFERENCES

[1] Fichter, K. (2005): Interpreneurship - Nachhaltigkeitsinnovationen in interaktiven Perspektiven eines vernetzenden Unternehmertums, Habilitation, Universität Oldenburg, Theorie der Unternehmung Nr. 33, Marburg: Metropolis-Verl.

[2] Brundtland Commission (1987): Our common future. Oxford paperbacks, Oxford: Oxford University Press.

[3] Herrmann, C. (2010): Ganzheitliches Life-Cycle-Management – Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen, Springer, Berlin, 2010, pp. 149-150

[4] Herrmann, C.; Kara, S.; Thiede, S.; Luger, T., Energy Efficiency in Manufacturing – Perspectives from Australia and Europe, In: 17th CIRP International Conference on Life Cycle Engineering (LCE2010), Hefei, China, 2010, pp. 23-28, ISBN 978-7-5650-0186-4.

[5] Bünting, F.: Lebenszykluskostenbetrachtungen bei Investitionsgütern. In: Schweiger, S. (Hrsg.): Lebenszykluskosten optimieren. Paradigmenwechsel für Anbieter und Nutzer von Investitionsgütern. 2009, pp. 35–50

[6] VDI (2005): Guideline 2884 – Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC).

[7] Thiede, S.; Spiering, T.; Kohlitz, S.; Herrmann, C.; Kara, S. (2012): Dynamic Total Cost of Ownership (TCO) Calculation of Injection Moulding Machines, In: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Berkeley, USA, Springer, 2012, pp. 275-280, ISBN 978-3-642-29068-8

[8] Life cycle assessment – requirements and guidelines DIN EN ISO 14044:2006, DIN October 2006

[9] Lu, T. et. al.: A Framework of Product and Process Metrics for Sustainable Manufacturing, in: Proceedings of the Eighth Global Conference on Sustainable Manufacturing, Abu Dhabi, 2010.

[10] Sustainability Reporting Guidelinesv3.1, Global Reporting Initiative, Amsterdam, 2000-2011.

[11] www.emc2-factory.eu

[12] Müller, F.: Classification Of Factories From A Green Perspective: Initial Guidance And Drivers For "Green Factory Planning", In: Proceedings of the 10th Global Conference on Sustainable Manufacturing (GCSM2012), Istanbul, Turkey, 2012.

[13] Herrmann, C., Thiede, S.: Process chain simulation to foster energy efficiency in manufacturing, In: CIRP Journal of Manufacturing Science and Technology, Elsevier, 2009.

[14] Stahl, B. et. al.: Combined Energy, Material and Building Simulation for Green Factory Planning, In: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering (LCE2013), Singapore, 2013.

[15] Thiede, S.: Energy Efficiency in Manufacturing Systems. Berlin: Springer-Verlag, 2012

[16] www.pe-international.com/services-solutions/green-building/building-lca/

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

15.6 Sustainability evaluation using a metrics-based Product Sustainability Index (*ProdSI*) methodology – A case study of a consumer electronics product

M. Shuaib, K. D. Seevers, T. Lu, F. Badurdeen, I. S. Jawahir
Institute for Sustainable Manufacturing, University of Kentucky, U.S.A

Abstract
As the demand for sustainable products increases, developing a capability to evaluate the sustainability content in manufactured products becomes significant and timely. This paper presents the application of recently established metrics-based Product Sustainability Index (*ProdSI*) methodology for evaluation of product sustainability by presenting a case study of a consumer electronics product. Two generations of the product manufactured by an international consumer electronics company are evaluated and compared for the sustainability content, by applying a comprehensive set of metrics across the total product life-cycle. The older generation is set as a benchmark for normalizing the selected relevant metrics. These product sustainability metrics are weighted and aggregated to calculate the *ProdSI* and to compare the sustainability performance of the two product generations.
Keywords:
Sustainable Manufacturing, Product Metrics, Life-cycle, Case Study, Consumer Electronics

1 INTRODUCTION

Current global trends of stricter environmental regulations, customer preference for sustainable products, potential depletion of non-renewable resource and inadequacy of some renewable resources are leading to an increasing demand for more sustainable products. In addition to the customers or end-users, the demand for more sustainable products is driven by the interests of all stakeholders throughout the product's life-cycle.

Sustainable products are defined as those products that provide environmental, societal and economic benefits while protecting public health, welfare and the environment over their full commercial cycle, from the extraction of raw-materials to final disposition [1]. According to this definition, the three aspects of the Triple Bottom Line (TBL) must be considered: economy, environment and society [2]. Achieving product sustainability also requires considering the total product life-cycle throughout the pre-manufacturing, manufacturing, use and post-use stages. During the product's life-cycle, the 6R method must be considered as an important approach to achieve the ideal case of perpetual material flow by applying reduce, reuse, recycle, recover, remanufacture and redesign activities across the product life-cycles [3].

Designing and manufacturing sustainable products requires the ability to assess the sustainability performance of products in a comprehensive and quantitative method that incorporates the key product sustainability concepts mentioned earlier; the assessment must cover the three aspect of the TBL and include an assessment of the 6R activities over the four life-cycle stages of the product.

This paper focuses on the assessment of a consumer electronics product with a proposed metrics-based methodology, namely the Product Sustainability Index (*ProdSI*). The metrics set is customized for the type of product under discussion. The assessment presented evaluates the sustainability performance of two generations of the product. Taking the older generation product as the benchmark, a comparative evaluation of the two generations is given based on a careful aggregation of collected data for the metric set by normalization and weighting. The results of the analysis are presented and discussed.

2 PRODSI METHODOLOGY

Early work by Jawahir et al. [4] presented a metrics-based product sustainability index (PSI) considering the total product life-cycle and the three aspects of the TBL. The PSI was based on the six key elements for product sustainability: environmental impact, resource utilization and economy, manufacturability, functionality, societal impact and recyclability/remanufacturability. The PSI methodology was applied by Ungureanu [5] and De Silva et al. [6] for product sustainability evaluation in automotive and consumer electronics products, respectively.

The Product Sustainability Index (*ProdSI*) methodology was later developed to expand the PSI methodology by identifying a comprehensive set of product sustainability metrics more systematically to incorporate the four product life-cycle stages and include the 6R application [7]. The *ProdSI* methodology was also applied to two industrial case studies in the automotive and consumer electronics industries [7, 8].

This paper applies the *ProdSI* methodology for product sustainability assessment for another consumer electronics product manufactured by an international manufacturer. The following is a brief explanation of the *ProdSI* methodology. More details on the methodology can be found in work by Zhang et al. [8, 9] and Shuaib et al. [7].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2.1 Hierarchical Structure of *ProdSI*

The *ProdSI* was developed in a hierarchical approach that breaks down the overall product sustainability to individual product sustainability metrics in a five-step process [7]:

1. *ProdSI* – the overall aggregated product sustainability performance index
2. Sub-index – the three aspects of the TBL
3. Cluster – major elements or factors of product sustainability in each of the TBL aspects
4. Sub-cluster – decomposition of clusters to more specific aspects of product sustainability
5. Individual metric – a quantifiable and measurable attribute or property related to a single parameter or indicator of product sustainability assessed throughout the four product life-cycle stages

The hierarchical approach was followed to systematically and comprehensively identify the individual metrics related to product sustainability. In addition, this approach allows the individual metrics to be customized for specific products, industries or applications. The top three levels of *ProdSI* are presented in Table 1.

Table 1: Product sustainability clusters.

Index	Sub-Index	Cluster
ProdSI	Economy	Initial Investment
		Direct/Indirect Costs and Overheads
		Benefits & Losses
	Environment	Material Use and Efficiency
		Energy Use and Efficiency
		Other Resources Use and Efficiency
		Wastes & Emissions
		Product End-of-Life
	Society	Product Quality and Durability
		Functional Performance
		Product EOL Management
		Product Safety and Health Impact
		Product Societal Impact Regulations and Certification

2.2 *ProdSI* Evaluation

While the individual product sustainability metrics provide a measure of performance along various dimensions related to sub-clusters, they do not directly provide an overall assessment of the overall product sustainability. The *ProdSI* methodology provides an approach to assess the overall product sustainability in a three-step process [7]:

1. Normalization – converting heterogeneous individual metrics to a normalized scale from 0 to 10 so they can be aggregated
2. Weighting – assigning individual weights to each element in the *ProdSI* hierarchical structure to balance the normalized values based on their relative importance or level of impact
3. Aggregation – bottom-up approach to aggregate the weighted normalized individual metrics up to the *ProdSI*

Several normalization and weighting methods are applicable, depending on the application, and are presented in [7]. The *ProdSI* evaluation methodology is illustrated in Figure 1.

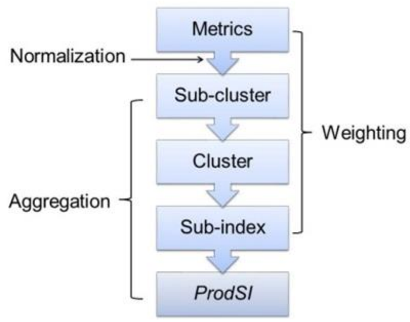


Figure 1: *ProdSI* evaluation methodology [8].

3 CASE STUDY

The case study presented was applied at an international consumer electronics products manufacturer. The company reports 100% of the GRI (Global Reporting Initiative) performance indicator topics in its Corporate Social Responsibility (CSR) report and is listed in the Dow Jones Sustainability World Enlarged Index (DJSI World Enlarged).

The case study applied the *ProdSI* methodology to assess and compare the overall sustainability performance of two generations of the same product. Due to confidentiality agreements, the details of the product and the company involved in the case study cannot be presented. The company will be referred to as the OEM (original equipment manufacturer) and the two product generations will be referred to as Gen1 and Gen2.

3.1 Individual Metrics Evaluation

The individual product sustainability metrics were customized for consumer electronics products based on feedback from the OEM. These metrics were evaluated for the two product generations throughout their four life-cycle stages. Metrics were calculated using input from product design, suppliers, manufacturing operations, CSR reporting, life-cycle assessment (LCA), customer service and recycling and remanufacturing operations. Since the two products deliver different functional capacities (Gen 2 delivers about 3.7 times the functional capacity of Gen1), the individual metrics were adjusted to reflect 3.7 units of Gen2 versus 1 unit of Gen1 to match the use stage of the two product generations. Table 2 presents a sample of the individual metrics for the two product generations.

Table 2: Sample individual metrics measurement for the two generations.

Sub-Index	Cluster	Sub-Cluster	Individual Metric	Unit	Metrics Measurement		
					Gen1	Gen1 adjusted	Gen2
Economy	Direct/Indirect Costs and Overheads	Labor Cost	Labor Cost	$	0.22	0.81	0.70
				$	0.32	1.18	0.64
		Material Cost	Material Cost	$	1.62	5.99	2.26
				$	6.37	23.57	12.75
		Energy Cost	Energy Cost	kWh	0.008820	0.032634	0.008820
Environment	Material Use and Efficiency	Product Material Content	Total Product Material Use	g	25	92.5	50
			Recycled Material Ratio of Product	%	0	0	60
			Mass of Restricted/ Hazardous Material	g	0.00	0.00	0.00
	Energy Use and Efficiency	Energy from Non-renewable Resources	Petroleum	l	0.00093	0.003441	0.00093
			Natural Gas	m^3	0.000025	.0000925	0.000025
	Other Resources Use and Efficiency	Water Use	Mass of Water Used	m^3	0.0013	.00481	0.0013
	Waste & Emissions	Gaseous Emissions	Greenhouse Gases	mTons	0.00025	0.000925	0.00025
		Solid Waste	Mass of Solid Waste Landfilled	kg	0.00097	0.003589	0.00097
	Product End-of-life (EOL)	EOL Product Recovery	Ratio of EOL Product Recovered	%	10-15	10-15	10-15
		EOL Product Remanufacturing	Ratio of EOL Product Remanufactured	%	0	0%	0%
		EOL Product Recycling	Ratio of EOL Product/Material Recycled	%	100	100%	100%
Society	Product Durability and Quality	Product Reliability	Failure Rate	%	0.20	0.20	0.20
			Life Span	yrs	5	5	5
	Product Safety and Health Impact	Safety	Injury Rate	#	0	0	0

4 *PRODSI* EVALUATION

The individual metrics measurements were used to calculate and compare the *ProdSI* for the two product generations. According to the *ProdSI* methodology, the metrics were normalized, weighted and aggregated to calculate the overall sustainability performance.

4.1 Normalization

The case study involved the evaluation of two product generations, Gen1 was selected as a base for the sustainability evaluation process. Since the metrics are normalized to a scale from 0 to 10, the score of 5 was selected as the base measurement and assigned to Gen1 adjusted normalized metrics. The individual metrics for Gen2 were normalized according to Equation 1.

$$\bar{x}_2 = 5 \times \left(1 + \left(\frac{x_2 - x_1}{x_1}\right) \times (-1)^n\right) \qquad (1)$$

where, n = 0 if the metric is directly proportional to sustainability performance

= 1 if the metric is inversely proportional to sustainability performance

x_1 is the adjusted metric measurement for Gen1

x_2 is the metric measurement for Gen2

$\bar{x}_2$ is the normalized metric measurement for Gen2

Packaging material use can be used as an example to the normalization process. The metric measurements for Gen1 and Gen2 are 21.46g and 5.80g, respectively. Since this individual metric is inversely proportional to sustainability performance (i.e. as packaging material increases, sustainability performance decreases), n = 1 in this case. Applying Equation 1 results in normalized values of 5.0 and 8.6 for Gen1 and Gen2, respectively, as illustrated in Figure 2.

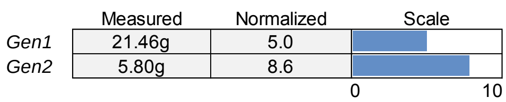


Figure 2: Measured and normalized values for packaging material use.

It should be noted that some metrics were normalized based on regulations and standards, best- and worst-case scenario, and expert assessment as explained in [7].

4.2 Weighting

The three sub-indices were considered to have equal level of weights. The weighting at other levels varied and was assigned using input from an industry expert representing the OEM. As a result the weighting was subjective, but it represented the level of importance of each sustainability element to the OEM and the relative ranking.

4.3 Aggregation

After collecting the data for individual metrics for both generations and completing the normalization and weighting processes, the *ProdSI* was calculated for the two product generations. The results and analysis are presented next.

5 RESULTS

The following is a summary of the calculations. The discussion is presented for the cluster and sub-index levels due to space constraints. The assessment was made using the adjusted metrics for Gen1 and the measured values for Gen2. The calculations for the sub-cluster, cluster, sub-index and *ProdSI* levels are presented in Table 3.

5.1 Economy

Initial Investment: captures the capital, research and development (R&D) and initial employee training expenses. For this cluster, Gen1 and Gen2 had normalized scores of 5.00 and 5.38, respectively. This is due to a reduction in initial employee training cost.

Direct/Indirect Costs and Overheads: sums the production costs per unit including labor, materials, energy, logistics and legal costs. For this cluster the scores were 5.00 and 7.46 for Gen1 and Gen2, respectively. The difference in the production costs is not significant when considering one unit of each of the two generations. However, since the comparison was adjusted to match the use stage of the two generations, the difference was multiplied by 3.7, and hence the significant improvement in this cluster for Gen2.

Benefits & Losses: considers the market value and the quality losses. Gen1 and Gen2 scored 5.00 and 6.70 in this cluster, respectively. The reason is the improvement in market value (again, here the adjustment factor of 3.7 was considered) and the decrease in warranty costs.

It should be noted that the normalization for the elements in this sub-index were done at the cluster level since the metrics were homogeneous and could be directly aggregated; they were all measured in $/unit.

The three clusters were weighted equally, and the scores for the Economy sub-index were 5.00 and 6.52 for Gen1 and Gen2, respectively.

5.2 Environment

Material Use and Efficiency: considers the total amount of material used, material utilization and standards and regulations related to material use. The scores in this cluster for Gen1 and Gen2 were 6.57 and 7.91, respectively. This is because less material is used to manufacture Gen2 versus the adjusted value of material use for Gen1.

Energy Use and Efficiency: takes into account energy use (from both renewable and non-renewable sources) and regulations and certifications related to energy use. In this cluster, the scores for Gen1 and Gen2 were 5.00 and 8.65, respectively. This is due to the improvement of production energy per unit of Gen2 after applying the adjustment factor.

Other Resources Use and Efficiency: in this case study, this cluster focused on water use. The OEM estimated that an equivalent amount of water was consumed for the production of a single unit. Therefore, after applying the adjustment factor, the scores for Gen1 and Gen2 were 3.15 and 4.97, respectively. Both scores were below 5 because of the low ratio of recycled water use.

Waste & Emissions: considers gaseous, solid and liquid wastes and emissions, regulations compliance and certification. The scores in this cluster for Gen1 and Gen2 were 6.21 and 8.26, respectively. The improvement was due to a drop in waste and emissions in Gen2.

Product End-of-Life (EOL): in this case study, this cluster considered product recovery, recycling, regulations and certification. The OEM engages in recycling operations, and the product recovery rates were found to be identical for both generations. As a result, the scores were identical for both generations; 3.42. The scores were below 5 because the products were not reused or remanufactured, which are two key parts of the 6R approach.

Based on the OEM's ranking and assessment of the importance of each cluster, Waste and Emissions and Product EOL were assigned the highest weights of 0.27 because of the clusters' direct link to key regulations, which are considered major drivers in the consumer electronics industry. The scores for the Environment sub-index were 5.14 and 6.32 for Gen1 and Gen2, respectively.

5.3 Society

Product Quality and Durability: considers product repair and maintenance, product reliability and product returns and recalls. The scores were 5.00 and 5.61 for Gen1 and Gen2, respectively. The improvement in Gen2 was due to a design change for Gen2 that improved repairability.

Functional Performance: this cluster considered major product specifications, functional effectiveness and ease of operation. The scores were 5.00 and 6.60 for Gen1 and Gen2, respectively. The improvement in this score was also due to a change in the design change for Gen2 that improved the functional effectiveness.

Product EOL Management: this cluster considered the ease of product disposal for the user and the ease of product recovery by the OEM. Both generations had a score of 5.

Product Safety and Health Impact: considers both immediate safety impacts and long-term health impacts. Both generations had a score of 7.5.

Product Societal Impact Regulations and Certification: considers product EOL regulations compliance and certification. Both generations had a score of 10.

The OEM considered the clusters in the Society sub-index to be equally important and assigned equal weighting. The scores were 6.50 and 6.94 for Gen1 and Gen2, respectively. The weighted sums of the clusters were assessed to calculate the sub-indices and the *ProdSI* for the two product generations. The overall *ProdSI* score was 5.55 for Gen1 and 6.59 for Gen2. These results show a significant improvement in the overall sustainability performance in

Table 3: *ProdSI* evaluation for Gen1 and Gen2.

Index	Gen 1	Gen 2	Sub-index	Gen 1	Gen 2	Cluster	Weight	Gen 1	Gen 2	Sub-cluster	Weight	Gen 1	Gen 2
ProdSI	5.55	6.38	Economy	5.00	6.52	Initial Investment	0.33	5.00	5.38	Capital Cost		$1.45	$1.52
										R & D Cost		-	-
										Employee Training		$0.46	$0.25
						Direct/Indirect Costs and Overheads	0.33	5.00	7.46	Labor Cost		$2.00	$1.34
										Material Cost		$30.75	$15.35
										Energy Cost		-	-
										Logistic Cost		$0.48	$0.21
										Product Operational Cost		$0.09	$0.04
										Legal Cost		-	-
						Benefits & Losses	0.33	5.00	6.70	Market Value		$125.80	$84.00
										Quality Losses		$9.25	$5.00
			Environment	5.14	6.07	Material Use and Efficiency	0.20	6.57	7.91	Product Material Content	0.67	4.85	6.87
										Material Utilization			
										Regulations and Certification	0.33	10.00	10.00
						Energy Use and Efficiency	0.13	6.25	7.16	Energy From Renewable Sources	0.25	0.00	0.00
										Energy From Non-renewable Sources	0.25	5.00	8.65
										Energy Regulations and Certification	0.50	10.00	10.00
										Energy Efficiency	-	-	-
						Other Resources Use and Efficiency	0.13	3.15	3.15	Water Use	0.50	5.00	5.00
										Recycled Water Use	0.50	1.30	1.30
										Other Natural Resources	-	-	-
										Natural Resource Regulations and Certification	-	-	-
						Waste & Emissions	0.27	6.21	8.26	Gaseous Emissions	0.18	5.00	8.65
										Solid Waste	0.27	5.00	7.65
										Liquid Waste	0.18	5.00	8.65
										Other Waste & Emissions	-	-	-
										Waste Management Regulations and Certification	0.36	8.33	8.33
						Product End-of-Life	0.27	3.42	3.42	EOL Product/Material Recovery	0.20	3.64	3.64
										EOL Product Reuse	0.20	0.00	0.00
										EOL Product Remanufacturing	0.20	0.00	0.00
										EOL Product Recycling	0.20	5.63	5.63
										Product EOL Regulations and Certification	0.20	7.86	7.86
			Society	6.50	6.54	Product Quality and Durability	0.20	5.00	3.62	Product Repair and Maintainance	0.30	5.00	7.00
										Product Reliability	0.35	5.00	4.29
										Return and Recall	0.35	5.00	0.00
						Functional Performance	0.20	5.00	6.60	Major Product Specifications	0.33	5.00	5.43
										Product Customizability	-	-	-
										Product Functional Effectiveness	0.33	5.00	9.37
										Ease of Operation	0.33	5.00	5.00
						Product EOL Management	0.20	5.00	5.00	Ease of EOL Activities	1.00	5.00	5.00
										Product EOL Societal Impact	-	-	-
						Product Safety and Health Impact	0.20	7.50	7.50	Safety	0.50	7.50	7.50
										Health	0.50	7.50	7.50
						Product Societal Impact Regulations and Certification	0.20	10.00	10.00	Product EOL Regulation Compliance	0.56	10.00	10.00
										Product EOL Certification	0.44	10.00	10.00

Gen2. As mentioned earlier, the improvement was mainly due to two factors: an increase in the functional capacity of the product in Gen2 and a change in the product design to improve product repairability and functional effectiveness.

Figure 3 presents the calculated scores for the thirteen clusters and clearly illustrates the areas of improvement in the overall sustainability performance of Gen2 when compared to Gen1.

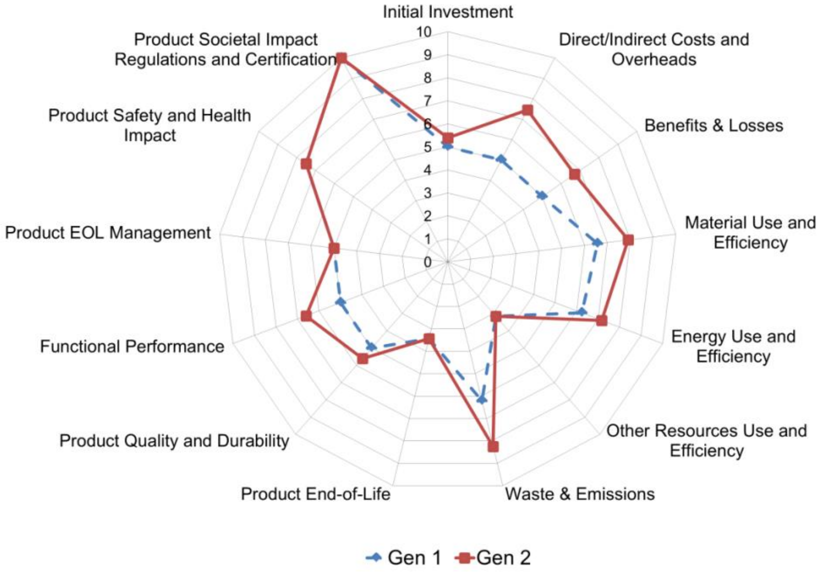


Figure 3: Calculated values of clusters for Gen1 and Gen2

6 CONCLUSIONS

This paper presented the application of a metrics-based product sustainability assessment methodology (*ProdSI*). The methodology was applied to two generations of a consumer electronics product, with the older generation serving as a benchmark for the assessment. Individual product sustainability metrics were measured, normalized, weighted and aggregated to calculate the *ProdSI* for the two product generations. Results show an improvement in overall product sustainability in the second generation. The improvement is mainly due to a change in the product design that led to improved functional capacity, repairability and functional effectiveness in the second generation.

7 ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the valuable input from individuals representing the OEM and the consumer electronics industry during the data collection and analysis of the presented case study.

8 REFERENCES

[1] Sustainable Products Corporation, Available: http://www.sustainableproducts.com/susproddef.html.

[3] Elkington, J. 1998. Cannibals with forks: the triple bottom line of 21st century business. New Society Publishers.

[2] Joshi, K.; Venkatachalam, A.; Jawahir, I.S. (2006): A New Methodology for Transforming 3R Concept into 6R Concept for Improved Product Sustainability, Proc. IV Global Conf. Sust. Prod. Dev. & LCE, São Carlos, Brazil, October, 3-6.

[4] Jawahir, I.S.; K.E. Rouch; O.W. Dillon; Jr., K.J.; Joshi, A. Venkatachalam and I.H. Jaafar, (2006): Total Life-cycle Considerations in Product Design for Manufacture: A Framework for Comprehensive Evaluation, (Keynote Paper), Proc. TMT 2006, Lloret de Mar, Barcelona, Spain, September 2006, pp. 1-10.

[5] Ungureanu, C.A., Das, S. and Jawahir, I.S., 2007. Development of a sustainability scoring method for manufactured automotive products: A Case Study of Auto Body Panels", Proc. IMECE ASME Int. Mechanical Engineering Congress and Exposition, Seattle, WA, IMECE2007-43818.

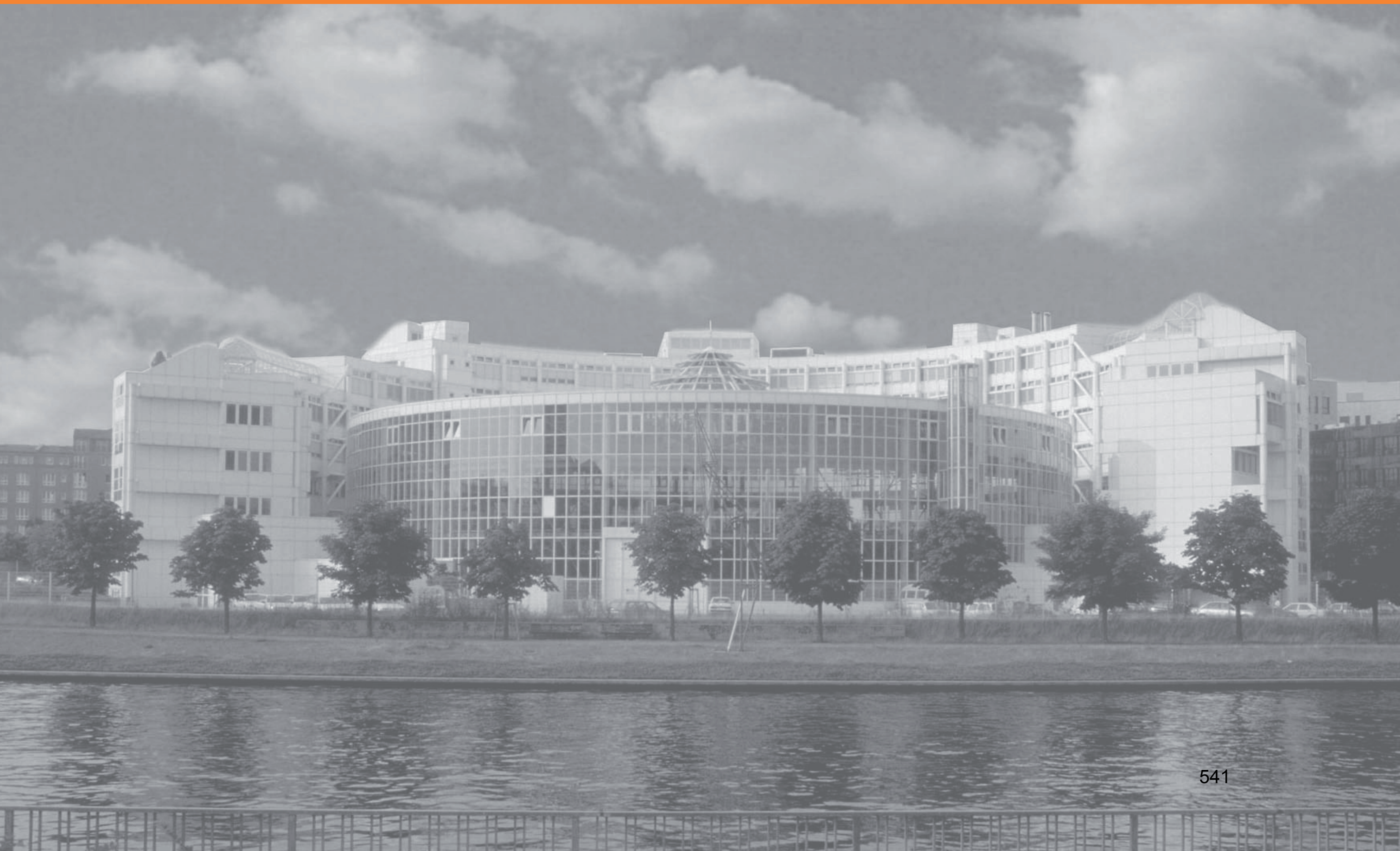
[6] De Silva, N., I. S. Jawahir, O. W. Dillon Jr., and M. Russell. 2009. A new comprehensive methodology for the evaluation of product sustainability at the design and development stage of consumer electronic products. International Journal of Sustainable Manufacturing 1(3): 251 - 264.

[7] M. Shuaib, F. Badurdeen, K. Rouch, S. Feng, I.S. Jawahir. Product Sustainability Index (ProdSI) – A Metrics Based Framework to Evaluate the Total Life-cycle Sustainability of Manufactured Products, manuscript submitted to JIE.

[8] Zhang, X., Lu, T., Shuaib, M., Rotella, G., Huang, A., Feng, S. C., Rouch, K., Badurdeen, F. and Jawahir, I. S. 2012. A metrics-based methodology for establishing product sustainability index (ProdSI) for manufactured products. In Leveraging Technology for a Sustainable World (Edited by D. A. Dornfeld and B. S. Linke): 435-441. Springer Publishers.

[9] X. Zhang, M. Shuaib, A. Huang, S.C. Feng, K. Rouch, F. Badurdeen, I. S. Jawahir. Total Life-cycle Based Product Sustainability Improvement: End-of-life Strategy Analysis for Metallic Automotive Components, 10th Global Conference on Sustainable Manufacturing (GCSM), Istanbul, Turkey, October 31 – November 02, 2012.

Session 16
Sustainability Assessment



GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

16.1 Towards a factory eco-efficiency improvement methodology

P. Ball, S. Roberts, A. Davé, H. Pimenta
Manufacturing and Materials Department, Cranfield University, Cranfield, UK

Abstract
The industrial system consumes a considerable amount of resources in the manufacture of products impacting on the environment generally and the production of CO2 specifically. Manufacturers have recognised the need for efficiency since their inception and placed emphasis on particular resource efficiency according to prevailing pressures. Energy and other resource efficiency are receiving particular attention in the current era and there are numerous examples of companies making significant improvements. Despite the successes there is a scarcity of published procedures and methodologies to guide a company through eco-efficiency improvements. This paper reviews available methods for energy and other resource reduction and presents generalised methodology that contains process steps and guidance for identifying improvement opportunities.

Keywords:
Eco-efficient improvement methodology, energy reduction, factory modeling, resource efficiency

1 INTRODUCTION

Significant improvements have been made to production systems over the centuries and in particular over the last five to six decades through the implementation of tools and techniques now commonly packaged under the label of lean manufacturing. These recent advances have been in the response to time pressures and product material waste.

Typically energy, water and other resources used to support the primary production have not been measured by operations in discrete production as they have been seen as 'free issue'. As a result the advances in primary material flow have not been replicated for the resources that support production. Until recently, improvements have been made as a consequence of production improvements rather than as a result of them being the primary objective.

As companies come under environmental and cost pressures to reduce energy, water and other resource consumption, targets have been introduced both at a business level as well as at factory and value stream level. The lack of experience and business as usual of reducing supporting resource flows presents difficulties for improvement engineers to identify resource reduction opportunities and implement them. An improvement methodology focused on energy, water and other utility resources would help engineers structure and perhaps be more effective in their projects.

This paper reviews improvement methods in general as well as those focused on energy and identifies opportunities to combine their features into a factory eco-efficiency improvement methodology. The high level steps of the methodology are presented and discussed. Reference is made to the features by using examples from industrial cases. The improvement method draws significantly from generalized production improvement methods currently practiced.

2 METHOD

The approach used for this research work was to review the features and benefits of improvement approaches published in both the general manufacturing arena as well as those specifically targeted at energy and other resource reduction. The focus is improvement of existing systems and is biased towards discrete production systems that could feature process plant within them. Learning from the challenges of improvement work by the authors is also included. The scope is deliberately broad from the initial motivation to make improvements in a factory to the implementation of specific changes.

In reviewing the improvement approaches, key features of a methodology are identified. An improvement methodology is proposed and justified through the literature review. The issues for its deployment area are assessed by illustrating challenges of particular industrial projects.

3 LITERATURE

3.1 Improving factory efficiency

Significant attention has been given to primary material flow in discrete production systems and significant advances have been achieved. Since the oil shock of the 1970s there has been a greater focus on energy but until recently resources such as energy have generally been seen as free issue in factory operations.

There have been many improvement methodologies that manufacturers have used to improve the efficiency of their operations. The most well-known ones relate to improving forward flow of product materials. Lean approaches focus on flow and reduction of direct waste [1, 2] whilst six sigma type approaches [3] aim to minimise variation. In addition there are other approaches such as the theory of constraints [4] that seek to maximise throughput.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

3.2 Lean and green

Improvement methodologies that relate to wider resource efficiency are less well known and tend to use the above approaches as a starting point. Resource efficiency relates directly to the waste reduction characteristics of lean and therefore is an appropriate starting point boarder objectives. It is notable that Kissock [5] and others [6, 7] have described how a side effect of implementing lean can be a reduction in energy, but there is little evidence from the literature that organisations are using approaches such as lean for targeting energy reduction as the primary focus. Attention is now increasingly being given to the environment and how manufacturing can be more sustainable [8] through reducing the use of all resources, not just material resources.

Whilst sustainable manufacturing practices are compatible with lean, primarily through waste reduction, it is not a given that lean practices will improve environmental performance [9]. However, it is significant that companies long associated with lean such as Toyota are now making significant reductions in energy, water and waste to landfill.

Sustainable manufacturing considers the entire material cycle from material extraction to subsequent disposal beyond the boundaries of a single factory [10]. Developments have included the switch to more environmentally benign materials, using less material, reusing waste and avoiding harmful emissions. Industry has grown used to energy being cheap over several generations [11] and there is now the recognition that the economic design factors for production systems need to be revisited [12]. Pressures to undertake such activities have been driven by economics such as material and energy cost, regulatory requirements and incentives as well as social and consumer pressures. The drive to use less resource is implicitly compatible with lean production.

Some of the aspects of lean improvement methods such as training, teams, walk-through (go and see) and focus on flow are generic and could be applied to any improvement method. There are other aspects of lean that are less transferrable such as value stream mapping (VSM). Such mapping is valuable for is engagement of teams around a problem but the flow of a product group is not necessarily the appropriate boundary on which to base factory resource reductions by.

3.3 Energy and other resource reduction methods

The energy reduction work in industrial systems spans many domains. For example, peak load management [13]; energy efficient technology replacement [14]; machine energy improvement [15]; general factory system improvement [16]. The following discussion highlights key features from a range of improvement approaches published.

Gopalakrishnan et al [17] describe a process for plant-wide energy assessment from which technical energy improvement actions can be made. The process has detailed steps for the assessment and pays particular attention to the supporting utilities as they consume a significant amount of energy such as boilers, compressors and variable speed drives. Importantly the work accounts for staff training, specifies the use of walk through, uses mapping for the energy flows and uses estimating to combat limited data availability.

In the prototype methodology based on industrial ecology, Despeisse et al [18] describe material, energy and waste flow modeling using steps of understanding, mapping, quantitative modeling, simulation, improvement identification, implementation and evaluation. The waste hierarchy and the R's strategies feature strongly and the issues of data availability and granularity are discussed. The improvement identification used for the methodology draws on the 'what to do' through sustainable manufacturing practice library [19] and the abstraction of these into the 'how to do it' through sustainable manufacturing tactics [20].

Pimenta et al. [21] have focused on the implementation of cleaner production implementation. The study was based on a mass and energy balance, flow chart design and layout analysis. Optimization of raw materials and energy usage and decrease of waste were achieved within small and medium companies from Brazil.

Guidelines are developed by Smith & Ball [16] for modeling material, energy and waste flows using data from a case manufacturing facility. The 16 step process detailed features walk-through, brainstorming, validation and improvement modeling beyond the expected steps of data collection through to analysis. The issue of shared energy and waste process is tackled. Spreadsheets feature strongly in the analysis stage.

Theide et al [22] have developed a method for energy and resource efficiency that has been generalized for access by all companies, including small and medium-sized enterprises (SMEs). The approach contains a means of categorizing energy consumers to target the high consumers with technological solutions. The approach recognizes the dynamic (time-varying) nature of production systems and therefore the dynamic energy consumption and utilizes modeling to analyze that variation. Interestingly, the work presents the main characteristics of their method, akin to requirements, including the level of data detail and link to tools. They identify fields of production machines, production control and technical building services for potential actions. In subsequent work, Theide et al [23], although non-specific about the range of improvement measures, identify the need for a catalogue of improvement measures to support the identification of opportunities.

Using a sustainable manufacturing framework, Subic et al [24] focus on energy, material and water efficiency, specially to reduce use and optimize flow. A walk-through is a feature of their approach, as is the challenge of measurement to obtain data for analysis. They note the lack of well-established company-based decision making frameworks within the companies sampled.

Viere et al [25] present a modeling methodology based on material and energy flows. The work recognises the relationship (or lack of) between full and lower loads of production. A significant emphasis is placed on cost. Like other approaches here, the use of powerful graphical communication like sankey diagrams are deployed.

As would be expected for any general improvement approach, the energy efficiency approaches available, e.g. [17, 18, 23, 26] all share a general process of establishing scope, getting data, analyzing data and proposing improvements. Such phases are typical of improvement methods and can be readily related to the plan-do-check-act (PDCA) cycle [27] and define-measure-improve-analyse-control (DMAIC) method [28].

Few of the approaches place emphasis on opportunities to save energy by considering the behavior and practices within a factory as separate from technical change. For instance, the approaches consider how to save energy in a machine operation but do not place emphasis on the general factory energy use in relation to the production schedule. So whilst there is little or no value-add activity in factory there should be low energy use. In practice energy use many factories between shifts may not fall significantly. The analogy with the lean manufacturing philosophy can be made here: the flow of energy and other resources should align to value-add activities and waste should be minimized.

3.4 Eco-efficiency improvement methodology features

In reviewing existing energy efficiency and resource efficiency improvement methodologies there are a number of common as well as unique features. These features are gathered to support the identification general features below for a methodology that covers the technical equipment analysis requirements as well as the behavioral analysis and the general preparation for the improvement work.

- The project environment needs to be prepared by setting objectives, forming a team and training the team.
- Project management needs to recognize that organizational as well as technical barriers will be encountered.
- Scope of analysis needs to be clear from the outset and subsequent focusing should be encouraged. Scope should consider the lifecycle of the material, energy, water, etc flows rather than artificial organizational boundaries. This means that buildings, utilities and production systems may be considered together.
- Support for the generation of ideas through brainstorming, generic guidance as well as specific improvement examples for inspiration will help novice analysts. Such support could also help any analyst having to cope with a large problem space and large data volumes.
- The power of visualization from walk-throughs to graphical simulation as well as results preparation should be utilized where possible.
- Data preparation needs to account for the expense of obtaining data, its availability, its granularity and its cleanliness.
- The analysis needs to be layered to be quick and simple enough to allow ‘quick wins’ to be identified but also progressed with more sophisticated tools to explore further improvements.
- Commercial software can provide detailed analysis and powerful graphical preparation but low cost easy to use software such as spreadsheets should be also specified to account for company skill and spend restrictions.
- Tools such as the waste hierarchy should be used appropriate stages but care should be made not to prescribe sequence, e.g. tools like the waste hierarchy may be followed in progressive layers or it should be possible to jump to specific layers.
- The analysis of resource flows should not be just technical but by value as well, e.g. whether the resource flows are supporting value add to the business.
- Overall iteration to progressively analyse wider scope and more detail should be encouraged in order to provide opportunities for ‘quick hits’ prior to more involved, more sophisticated solutions.
- Assessment of solutions should recognize the factory metrics, e.g. a solution may not be cost effective but may help achieve a corporate energy reduction target.
- The stage-gating of a methodology will encourage engagement with sponsors as well as provide opportunities to stop unproductive projects. It will encourage verification of data and analysis throughout. In turn, projects that ‘fail’ should be documented to help others.

3.5 Summary

The aforementioned features are insufficient to provide a specification for an eco-efficiency improvement methodology. However, they do provide features to influence the development of a process that could support industry on their journey towards greater eco-efficiency. The points identified consider both soft (organisational) and hard (technical) aspects which contribute to the distinctiveness of this research work.

4 ECO-EFFICIENCY IMPROVEMENT METHODOLOGY

4.1 Overview

The factory eco-efficiency improvement methodology developed seeks to guide improvement of resource flows including material, energy and water to achieve lower environment impact. It is intended to reduce costs, assuming this is an objective. The methodology contains the steps typical of any improvement approach and contains the features identified earlier. Finally, it permits a compromise between data and tool availability with depth of analysis.

The main (level 0) stages are list follows whilst the level 1 detail of these stages is shown in Figure 1. Descriptions of each stage follow.

1. Understanding: Establishes the focus for an improvement project that will deliver resource efficiency advances.
2. Mapping. Provides a ‘high-level’ understanding of the processes within the factory context.
3. Data collection. Retrieves and analyses detailed (hourly/daily) building and process data.
4. Static analysis. Structures of data and analysis with a focus on the of application tactics.
5. Simulation. Detailed model building and simulation with a focus on data and application of tactics.
6. Completion. Reports options and plans implementation.

4.2 Understanding

The understanding stage contains the vital, though in practice not well documented, steps of team creation and education. An understanding of the potential organizational barriers [29] can lead to a more effective project team.

Example: a large aerospace manufacturer was able to gain an early appreciation of staff willingness to assist the project team in their objectives through knowing whether shop floor staff are rewarded for energy reduction.

The factory walk is an essential stage of understanding the factory operation. This must look inside and outside the factory as well as, if possible, on the roof. The aim is to understand what resources enter and leave the site, both as visible as well as invisible (e.g. heat) flows.

Example: an optical products manufacturer suspected that the painting area could be a potential area of focus. The factory walk covered the key production stages, especially those with large capital equipment installations, as well as around the outside of the factory for utilities and meter points.

The scope must be quickly defined and this will come from high level quick analysis, commonly confirming initial suspicions of where to focus. The analysis will use historic, static data and will tolerate errors as largest energy and other resource flows may quickly become apparent.

4.3 Mapping

Mapping is the qualitative first stage of two data gathering stages. It is intended to be a quick, graphical information gathering stage that captures the multiple resource flows from file stores or hand drawing on factory layout print outs. It is necessarily a messy stage. It should capture the resource flows as well as the metering points that will aid later quantitative data collection. It will engage a broad spectrum of staff through multiple shop floor visits.

From the early data collection it is expected a single concept model is created on paper that overlays multiple flows, metering points and establishes a clear boundary to indicate what is within and outside of scope. Early indications of the desired level of detail of data will form. An understanding of where portable metering will need to be positioned emerges and in turn triggers approval processes so installation can be scheduled according to maintenance windows.

Example: From various industrial cases it has become apparent that the mapping stage is relatively simple for primary material flows but there are difficulties of understanding other flows. This should consider which part(s) of the power network feeds particular machines and how lighting, compressed air and steam sub-circuits maps to building areas and product flows. Early indications of data collection and allocation difficulties emerge.

4.4 Data collection

In the second phase of collection, quantitative data collection aligning to the qualitative mapping takes place. Site meters for gas, power and water are quick high level sources of data, however, they contrast with the readily available detailed production flow and route data. Spreadsheets are typically used at this stage to store and prepare data. Sankey diagrams may be prepared at this stage to aid verification. By combining the data collected with the previous mapping the conceptual model can be validated. Challenges have been experienced at this stage.

Example: In one optical products company the data available at factory level from metering was readily available but then could not be broken down by building or building zone.

Example: In another aerospace company the detailed data was available from permanent and portable meters but the data had to be cleaned to remove rogue spikes and approximate missing time steps ready for analysis.

From the small sample of cases to date it appears that the older the factory and the more product layout changes that have taken place then the harder it is to gather consistent detailed data directly related to the focus area.

As with previous stages, improvement ideas are collected as they emerge but they are not progressed. Analysis needs to take place to assess these quantitatively as part of considering a range of possible solutions.

4.5 Static analysis

The static analysis is the first of two analysis stages. This stage assumes average conditions. This analysis stage may simply consider analysis of available factory data (e.g. comparing energy consumption against production output) or may involve model building (e.g. predicting likely resource consumption for different production schedules). Early cost analysis starts.

The modeling activity will use the conceptual model created earlier and place all available data into a single numerical model, most likely spreadsheet based. Collation and analysis of the data may prompt actions to gather missing or more detailed data. Sensitivity analysis can be carried out to understand the implications of input data that was estimated. The analysis stage can be progressively carried out with more and more detail to uncover solutions, some of which may seem obvious in retrospect. Success at this stage may mean the subsequent more sophisticated dynamic analysis stage is not required.

Insights from case work at this stage include the challenges of shared resources and the benefits of tackling soft behavioral as well as hard technical improvements.

Example: In one industrial products manufacturer, simple techniques were used to allocate air and power use by a machine shop that shared resources with other process in the same building without the need for additional metering.

Example: In another manufacturer changes to the way staff operated equipment enabled resource reductions without changes to machine operation or set points.

Inspiration for solutions at this stage can be obtained from the use of sustainable manufacturing tactics [20]. The tactics describe 'how' an improvement can be obtained by changing or managing the resource and/or the equipment. For example, managing equipment better by changing set points or changing a resource for a less polluting one. In turn, sustainable manufacturing practices [19] can be searched to obtain specific examples of 'what' other manufacturers have done. The use of tactics and practices are a means of helping users find potential solutions, a feature that is rare in improvement approaches.

4.6 Simulation

The simulation stage is the second and more complex of the two analysis stages. This stage considers the passage of time and therefore the issues associated with relative timing of resource use and waste generation by processes in different locations over the short and longer term. Depending on the success of the first analysis stage and the available software and skills it is possible that this stage may be skipped.

Software for modeling the building or the production area are commercially available in isolation but it is only development versions of tools like IES Virtual Environment (VE) that have combined functionality. The second issue for simulation here is the skill required to model across the breadth of buildings, utilities and production systems; few people have the breadth of such skills and production modelers are not used collaborative working (nor is the software set up for it) to permit combining skills specialization.

Example: simulation modeling of a paint plant where the flows of energy (electricity, gas and steam) are modeled over time applied tactics to automated searches for possible resource efficiency opportunities, such as when energy is being consumed but there is no product output.

Ultimately if the model scope was wide enough then tactics could identify opportunities to align waste generation from one process that is of the same form, timing and quality required by another process as input.

4.7 Completion

It can be argued that the completion stage is not unique in any improvement work and that the success factors and barriers in implementation are common. These could range from project management to leadership to change management.

The cost-benefit analysis is an aspect that could be considered standardized but the performance measurement system will influence. This can be illustrated in two contrasting cases.

Example: A plastics company that investigated closed-loop recycling within a product range. The equipment, storage and logistics costs for the low volume of material that could be captured meant the payback time was long.

Example: In an automotive manufacturer, the option of overtime to enable better energy management between shifts whilst costly was desirable as it helped achieve a publically promised absolute energy reduction.

What is important to add here is that resource efficiency practice is not widely understood across the engineering field in general and in within individual companies. Capturing the learning from each project is therefore an important aspect of closure. This will include the general lessons learnt but also cataloguing the specific practice improvements that can be shared internally to a company and potentially externally too.

5 CONCLUSIONS

This paper has argued that whilst there is a growing body of information on actions that companies have taken to improve the eco-efficiency of their factories, there are few public improvement methodologies that help explain the actions they undertook or that manufacturers can use to improve their operations. General as well as energy focused improvement approaches have been reviewed to capture key aspects of their approach and tools.

The research work undertaken has resulted in a set of features that can be used to specify an improvement method that can guide the data collection, analysis and idea generation. The improvement method attempts to combine both the project management aspects of improvement as well as technical analysis. Additionally, it has features that help to generate or source improvement ideas.

The key contribution of the paper is the creation of a generalized factory level eco-efficiency improvement methodology that brings together a breadth of guidance for creating and implementing resource efficiency actions. Future work is to generate a number of cases that demonstrate the strengths, and weaknesses, of the developed methodology across a number of resource efficiency applications to help guide further refinement.

6 REFERENCES

[1] Bicheno, J. 2000. The Lean Toolbox, 2nd ed., Picsie Books, Buckingham, UK.

[2] Womack, J.P., Jones, D.T., 2005, Lean solutions: how companies and customers can create value and wealth together, Simon & Schuster, London, UK.

[3] Pyzdek, T., 2003, The six sigma handbook, 2nd ed. McGraw Hill.

[4] Goldratt, E., Cox, J., 1996, The Goal (2nd ed.). Gower Pub Co.

[5] Kissock, K., Seryak, J., 2004, Lean Energy Analysis: Identifying, Discovering and Tracking Energy Savings Potential, Proc. SME, Livonia, MI, USA: 1–11.

[6] Kissock, K., Eger, C., 2008, Measuring industrial energy savings, Applied Energy, 85(5): 347–361

[7] Seryak, J., Epstein, G., D’Antonio, M., 2006, Lost Opportunities in Industrial Energy Efficiency: New Production, Lean Manufacturing and Lean Energy, Proc Industrial Energy Technology Conf, New Orleans, LA.

[8] Jovane, F., Yoshikawa, H., Alting, L., Boer, C.R., Westkamper, E., Williams, D., Tseng, M., Seliger, G., Paci, A.M., 2008, The incoming global technological and industrial revolution towards competitive sustainable manufacturing, CIRP Annals Manufacturing Technology, 57:641–659.

[9] Yang, M.G., Hong, P., Modi, S.B., 2011, Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing firms, Int J Production Economics, 129:251-261.

[10] O’Brien, C., 1999, Sustainable production - a new paradigm for the millennium. Int J Production Economics, 60-61:1-7.

[11] O’Callaghan P.W., Probert, S.D., 1977, Energy management, Applied Energy, 3:127–138.

[12] Karnouskos, S., Colombo, A.W., Lastra, J.L.M., Popescu, C., 2009, Towards the energy efficient future factory Industrial Informatics, INDIN 7th IEEE Int Conf: 367-371.

[13] Solding, P., Thollander, P., 2006, Increased energy efficiency in a Swedish iron foundry through use of discrete event simulation, Proc Winter Simulation Conference, 1971-1976.

[14] Energy Efficiency & Renewable Energy (EERE), 2010, Energy efficient solutions, accessed 14/05/13, http://www1.eere.energy.gov/manufacturing/pdfs/itp_successes.pdf

[15] Yan, J., Li, L., 2013, Multi-objective optimization of milling parameters - the trade-offs between energy, production rate and cutting quality, Journal of Cleaner Production (in press)

[16] Smith, L., Ball, P.D., 2012, Steps towards sustainable manufacturing through modelling material, energy and waste flows, Int J Production Engineering, 140/1:227-238.

[17] Gopalakrishnan, B., 2005, A Systems Approach to Plant-Wide Energy Assessment, Energy Engineering, 102/5:49–79.

[18] Despeisse, M., Ball, P.D. Evans, S., Levers, A, 2012, Industrial ecology at factory level: a prototype methodology, Proc IMechE Part B, Journal of Engineering Manufacture, 226/10:1648-1664.

[19] Despeisse, M., Mbaye, F., Ball, P. D., Evans, S., Levers, A., 2011, Emergence of sustainable manufacturing practices, Production Planning and Control, 23/5: 354-376.

[20] Despeisse, M., Oates, M.R., Ball, P.D., 2013, Sustainable manufacturing tactics and cross-functional factory modelling, J Cleaner Production, 42:31-41.

[21] Pimenta, H.C.D., Gouvinhas, R.P., Evans, S., 2011, Cleaner production as a corporate sustainable tool: a study of companies from Rio Grande do Norte state, Brazil. In: Global Conference on Sustainable Manufacturing, 11, Saint Petersburg, Russia

[22] Thiede, S., Bogdanski, G., Herrmann, C., 2012, A Systematic Method for Increasing the Energy and Resource Efficiency in Manufacturing Companies, in: CIRP Global Web Conf: Interdisciplinary Research in Production Engineering, 2/28–33:2212-8271

[23] Thiede, S., Posselt, C., Herrmann, C. 2013, SME appropriate concept for continuously improving the energy and resource efficiency in manufacturing companies. CIRP Journal of Manufacturing Science and Technology (in press)

[24] Subic, A., Shabani, B., Hedayati, M., Crossin, E., 2013, Capability framework for sustainable manufacturing of sports apparel and footwear sustainability, 4:2127-45.

[25] Viere, T., Stock, M., Genest, A., 2013, How to Achieve Energy and Resource Efficiency: Material and Energy Flow Modeling and Costing for a Small and Medium-Sized Company, Energy-related and economic balancing and evaluation of technical systems – insights of the Cluster of Excellence eniPROD, Proc workshop of cross-sectional group 1 “Energy related technologic and economic evaluation” of the Cluster of Excellence eniPROD, Wissenschaftliche Scripten, Auerbach.

[26] Brown, H.L., Shah, Y.T., 1996, Industrial plant process flow/energy analysis. In: Misra KB (ed.) Clean production: environmental and economic perspectives. Berlin: Springer: 647–683.

[27] Deming, W.E., 1992, The Deming Management Method, Mercury Business Books.

[28] George, M.L., Rowlands, D., Price, M., Maxey, J., 2005, The lean six sigma pocket toolbook, McGraw-Hill Professional, New York.

[29] Lunt, P., 2013, Barriers to Energy Reduction in Manufacturing, Cranfield University MSc Thesis.

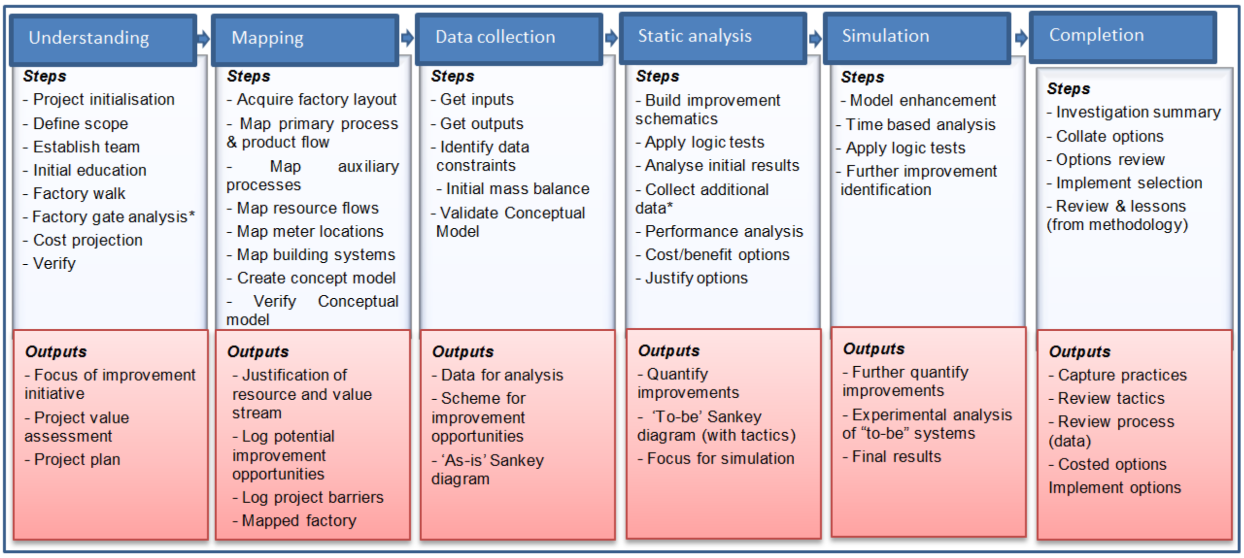


Figure 1: Detail of stages in the factory eco-efficiency improvement methodology

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

16.2 Monetary assessment of an integrated lean-/green-concept

G. Lanza [1], S. Greinacher [1], A. Jondral [1], R. Moser [1]

[1] wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Germany

Abstract

Energy and natural resource prices are subject to a rising tendency with increasing volatility worldwide. On account of growing demand and limited resources, companies are obliged to aim at minimum waste production. However, the forecast of effects of combined lean and green practices presents a major challenge. So far, they have predominantly been calculated, optimized, and assessed independently of one another. This paper introduces a methodology for a successive further development of lean and green production based on the proactive monetary assessment of combined effects of both lean and green strategies. The outlined approach covers data collection and evaluation of the current production system, calculation of relevant key figures of selected combinations of lean and green practices by use of a queuing theory based analytical material flow model, proactive monetary assessment of the analyzed combination, and deduction of a company-specific plan of measures.

Keywords:

Lean and green; monetary assessment; production system;

1 INTRODUCTION

Manufacturing Enterprises are facing rising prices for energy and natural resources in combination with escalating volatility. Monitoring the crude oil price per barrel demonstrates these ups and downs impressively: oscillating around $30 in the 1990ies, prices exploded to an all-time high of $120 in 2008 before dropping temporarily below $50 followed by a subsequent rise to currently $89 [1,2]. Similar tendencies can be observed studying the price per troy ounce of platinum during the past decade: starting from $500 in 2000, a maximum of $2.300 was reached in 2008 followed by a drop to $760 before increasing again to $1.500 in 2012. These tremendous variations in prices combined with a growing demand of energy and resources worldwide – the International Energy Agency predicts a rise of the global energy demand by at least 40% until 2035 – and limited resources – experts agree on having reached peak oil today – will result in further rising prices [1].

A survey published in October 2011 by "Commerzbank-Initiative Unternehmensperspektive" among 160.000 German companies concludes that approximately half of the medium sized companies expect negative impacts of globally rising resource demands on German economy. One third of the surveyed companies claim to experience negative effects by rising energy costs, 50% face difficulties due to highly volatile price developments of energy and resources [3]. Affected companies can react either by raising prices of their own products – currently performed by 42% of the interviewed companies – demanding additional quality features, e.g. shortened delivery time, to hold up customer satisfaction or by keeping prices steady, requiring reduced production costs. This can be achieved by improving production process efficiency, waiting and cycle times, quality rates, as well as resource and energy consumption by implementing lean and green practices to reduce waste.

However, the forecast of combined effects of both lean and resource efficient (green) practices is a major challenge. The majority of existing approaches concentrates on assessing lean strategies: either by simulation of their effects [4,5] or by analytical calculation of their impacts [6,7]. The modeling of green practices focuses prevailingly on energy consumption of machine tools [8], whereas only few approaches consider the effects of green manufacturing at shop floor level [9], and even less factor in scheduling flexibility and high product variety [10]. Based on the examination of effects of implemented lean practices on costs and energy consumption, Hermann et al. [11] developed a simulation to assess a combination of lean and green manufacturing.

2 OBJECTIVE

Especially small and medium sized enterprises do not possess sufficient financial and staff capabilities to invest in projects with uncertain outcome and compensate expenditures for the implementation of lean and green practices with minor effects [12]. Furthermore, they lack an easily adaptable guideline to identify necessary steps for a successive (further) development of their lean and green production system independently of expensive simulation tools and/or experts. This motivates the targeted consistent integration of the following approach and its tools into a decision support environment implemented in standard software.

This paper presents a methodology for the identification and evaluation of the most profitable combination of lean and green strategies to be implemented in a production system. This is achieved by proactive monetary assessment of the strategies' combined effects on key performance indicators, e.g., quality, delivery time, and manufacturing cost. Therefore, the quantified effects of combined lean and green practices are calculated with an analytical, queuing theory based

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

material flow model of the examined production system. By assessing key performance indicators and the required investment for implementation the most profitable combination of lean and green strategies is identified. Furthermore, the most efficient sequence of implementation is identified, resulting in a production system-specific plan of measures.

3 APPROACH

The presented approach for the assessment of lean and green production systems is structured into three succeeding phases: “Analysis”, “Configuration”, and “Interpretation”. Figure 1 illustrates the phases and their comprised tasks that are outlined in the following.

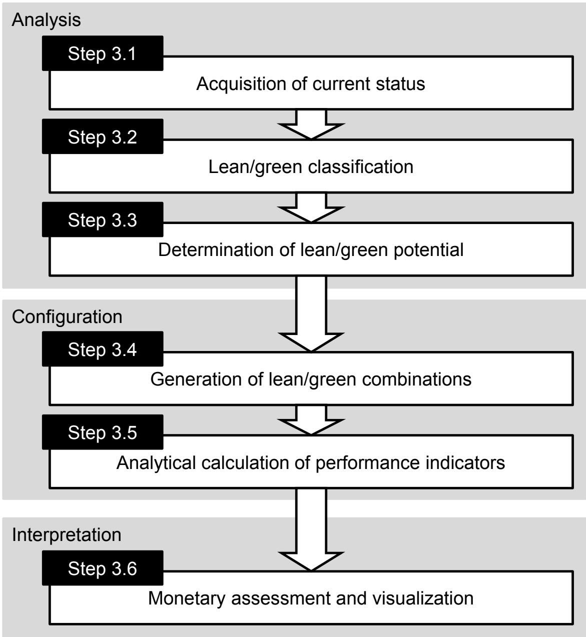


Figure 1: Procedure of solution.

Phase 1 “Analysis” contains acquisition of the assessed production system’s current status, classification of its current lean and green level by the application of maturity level models, and determination of its improvement potential.

Phase 2 “Configuration” encompasses the generation of discrete combinations of lean and green practices and their specific measures that are considered for implementation. Subsequently, the resulting effects of the identified combinations on performance indicators are evaluated with an analytical, time discrete queuing theory model of the examined production system.

The concluding phase 3 “Interpretation” covers visualization and monetary assessment of the examined combinations of lean and green strategies based on the calculation results of the production system’s analytical model.

3.1 Acquisition of current status

Initially, the relevant section for further examination of a production system is defined. Its characteristics are converted into a basic data model, serving as database for the following analysis and calculations.

The required data is gathered by conducting a combined value and energy stream mapping for representative products of the assessed production system. This allows visualization of processing steps, stocks, value- and energy streams, energy- and resource consumption, as well as the linkage of customers and suppliers. Thus, it contributes substantially to the overall understanding of the assessed production system and presents a suitable tool to specify and narrow down the examined section [13,14]. The primary results include the revelation of the system’s weak spots, the flow rate of production, energy intensities, as well as the efficiency of energy and resource input. Subsequent synchronization with documented information and processes serves as verification and important indicator for the selection of the most promising lean and green practices for later implementation.

In addition to value and energy stream mapping, the detailed modeling of a lean and green production system requires additional data. This encompasses information concerning system load, organizational data, e.g., work time regulations, processes, and allocation of resources, as well as technical data of the utilized machine park. Furthermore, controlling data, e.g., cost rates of machines and personnel as well as input of energy respectively resources are necessary to generate a solid data base [15].

3.2 Lean/green classification

Data acquisition is followed by the ranking of the assessed production system’s current lean and green level (respectively stage) by applying maturity level models of its lean and green practices.

Lean and green classification is performed for all relevant practices of the production system. Practices of interest depend on the respective system’s objectives and are selected by each enterprise individually. Maturity level models represent a convenient method for the classification of a practice by identifying its current stage (compare [16] for lean practices). Maturity level models consist of several consecutive stages. A certain stage of a lean or green practice is achieved as soon as all of the stage’s necessary requirements are sufficiently fulfilled [17], e.g., a certain amount of measures of the preceding stages are successfully implemented. To ensure general and cross-company applicability of the approach, absolute maturity models are favorable. Relative maturity models are only applicable when comparing production systems within the same enterprise. Figure 2 illustrates a schematic maturity level model for lean and green practices. It contains five consecutive stages: (1) initial, (2) planned, (3) defined, (4) measured, and (5) optimized according to maturity models in software development and business processes [18].

Lean/Green Practice				
initial	planned	defined	measured	optimized
no measures implemented	measures of stage 2	measures of stage 3	measures of stage 4	measures of stage 5

Figure 2: Schematic maturity level model (compare [18]).

3.3 Determination of lean/green potential

Following the classification of a production system’s lean and green practices, each practice’s theoretical and practical potential of improvement is identified. Subsequently, the most promising practices are selected for possible further development.

Following the identification of the production system's current lean and green level, its potentially achievable level is identified by determining theoretically achievable stages of its most promising lean and green practices. In addition the practices' impacts on performance indicators of the production system are estimated. Practices of interest are selected in due consideration of the system's requirements and objectives, as well as the expected potential of improvement. The potential of improvement corresponds to the deviation between a practice's current and theoretically achievable stage. Practices without potential of improvement do not require further pursuing.

Appropriate techniques for the identification of a practice's theoretical lean and green potential are benchmarking and expert consultation. Benchmarking identifies best-in-class values of comparable manufacturing systems in external enterprises. Expert consultation results in interviewing specialized employees such as manufacturing engineers and technicians.

For example, a production system's quality rate has been improved by 7% relative to its initial state by applying basic measures of the lean practice "Total Quality Management" (TQM). Therefore, it is currently ranked as TQM-stage 2. Nevertheless, the enterprise's production experts consider the future implementation of TQM-stage 5 as possible. Benchmarking among external enterprises, which are applying TQM-stage 5 indicates an average improvement of 28% in quality rate relative to the initial state (TQM-stage 1). This indicates a remaining potential of improvement in quality rate by 22.6% for the investigated production system relative to its current stage (improvement from TQM-stage 2 to TQM-stage 5).

With due regard to the ideally attainable parameters for each lean and green practice, actually realizable target values are defined for each parameter, e.g., a targeted improvement of quality rate by 15%. This is necessary, because the realization of a practice's advanced stages is not always reachable with justifiable effort and does not necessarily represent the best configuration for the assessed production system. E.g., one-piece-flow embodies the highest stage of the lean practice "Lot Size Reduction". Nevertheless, batch processing should be favored for certain processes, e.g., for heat treatment in annealing ovens.

3.4 Generation of lean/green combinations

After determining the theoretically and practically achievable potential of a production system and the selection of lean and green practices that are considered for further development, valid combinations of their comprised measures are identified and parameterized for further evaluation.

Therefore, specific measures capable of contributing to the achievement of the corresponding lean or green practice's target stage are selected. In order to allow analytical assessment, each measure's potential of improvement is quantified. According to the selection of potential practices, the identification and quantification of comprised measures is an enterprise-specific procedure that depends on the involvement and cooperation of the respective employees. Workshops present an appropriate method for employee integration and participation. E.g., due to expert consultation the implementation of the TQM-measure "quality gates in early production states" may amount to an additional 5% of quality rate improvement relative to the production system's initial state (TQM-stage 1). The cumulative potential of a practice's measures available on a certain stage may not exceed the respective overall potential of improvement obtained by benchmarking.

The following step encompasses the generation of all valid combinations of the available measures. This selection process is supported by a consistency check, which ensures the congruity of the generated combinations. By applying suitable minimum requirements and exclusion criteria the number of possible combinations is narrowed down substantially. Common criteria cover exclusion of measures with opposing effects and prescription of a chronological implementation order of measures that are dependent of one another. This process is based on a catalogue of action, which categorizes the measures' interactions. Figure 4 depicts an exemplary extract of interactions between selected lean measures and optimization objectives. In order to ensure the achievement of a practice's targeted stage the cumulated effects of a practice's selected measures have to fulfill its predefined target value. E.g. the defined target for quality improvement by implementing TQM amounts to 15%. Therefore, all combinations of its measures that do not reach the requested cumulative improvement are not valid and therefore excluded from further assessment.

optimization objective / optimization measure	output quantity	flexibility (quantity)	flexibility (time)	lead - and delivery time	adherence to delivery dates	rejection rate	capacity utilization	stock (receiving area)	stock (production)	stock (shipping area)
Production leveling (Heiijunka)	1	0	1	0	0	0	2	-1	-1	-1
Division of work	0	1	1	2	1	0	0	0	2	2
Just in time (JIT) delivery	0	-1	0	1	-1	0	0	2	2	2
Milkrun	0	0	0	0	0	0	0	2	2	0
One-Piece-Flow	0	1	2	1	1	0	-1	2	2	2
Continuous Improvement Process (CIP)	1	1	1	1	1	1	1	1	1	1
Poka-Yoke	0	0	0	0	0	2	0	0	0	0
Single-Minute Exchange of Die (SMED)	1	1	2	1	1	0	2	0	0	1
Total Productive Maintenance (TPM)	1	0	0	0	0	1	1	0	0	0

Figure 3: Exemplary catalog of action for lean measures and optimization objectives (positive correlation: 2 and 1, negative correlation: -2 and -1, no correlation: 0) (compare [19]).

3.5 Analytical calculation of performance indicators

The identified discrete combinations of lean and green measures are subsequently evaluated within an analytical material flow model of the assessed production system based on time discrete queuing theory. This allows the calculation of relevant performance indicators on the production system's material flow level, e.g., waiting and lead times of parallel servers [20]. Furthermore, interdeparture times, machine failures, and setup times can be approximated. The corresponding events are modeled realistically by the integration of stochastic variations of the respective input values, e.g., mean time between failures (MTBF) and mean time to repair (MTTR). The resulting performance indicators of the production system are specified by their respective distributions and quantiles.

To ensure the applicability of this approach in small and medium sized enterprises the material flow model and the additional tools presented in this approach are merged into an integrated assessment tool to realize a continuous decision support environment in easy to use standard software. The model's high reusability and easy reconfigurability is ensured by applying standardized modules of relevant material flow elements, e.g., a universal module for machining centers, as well as for lean and green measures. The impacts induced by the implementation of lean and green measures can be distinguished into parameter changes and structural changes. Parameter changes affect a certain input value by a defined percentage, e.g., improvement of quality rate by 5%. Structural changes either activate or deactivate components of the model, e.g., the application of production control strategies.

3.6 Monetary assessment and visualization

The majority of enterprises consider production cost the essential criteria of assessing a production system's lean and green configuration. Production costs include material purchase, direct labor, as well as manufacturing overhead [21]. "Cost-time profiles" (CTPs) present an intuitive tool to visualize production cost with respect to processing time. A CTP visualizes the increase in value of a product during manufacturing and allocates production steps to points in processing time. This includes consideration of the monetary implications of the following elements [22]:

1. Materials, in particular cost of raw materials and purchased parts
2. Activities, in particular cost of employment of machines and personnel, setups, and rework (cost rates)
3. Waiting between activities, in particular buffering before and after machining, storage, and transport (fixed capital)
4. Total cost per product per point in time (cumulated costs plus manufacturing overhead)

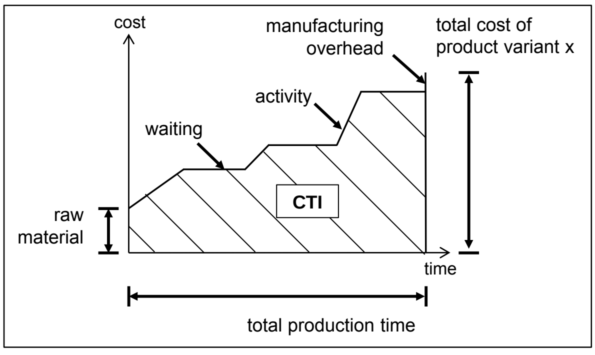


Figure 4: Components of a cost-time profile (compare [22]).

Additionally, CTPs allow the consideration of cost-time investment (CTI) for manufactured goods. The CTI corresponds to a product's total cost weighted with the period of time the money is locked up in stocks/production. By multiplying the CTI with its respective internal rate of return (IRR) the overall manufacturing cost incurred, including cost of capital lockup, besides the cost actually spent on the manufacture of a product (total cost) can be determined. Therefore, the CTI represents the figure that is influencing an enterprise's financial management.

The aggregated manufacturing cost of a product of variant *v*, including manufacturing overhead, can be calculated as follows [23]:

$$Manufacturing\ Cost_v = Total\ Cost_v * (1+m) + CTI_v * IRR \quad (1)$$

v:	product variant
m:	factor of manufacturing overhead
IRR:	internal rate of return
CTI:	cost-time investment

To calculate the production system's production cost over all product variants within a defined period of time, the respective variant's production cost are multiplied with the quantity of parts manufactured within the time period of interest.

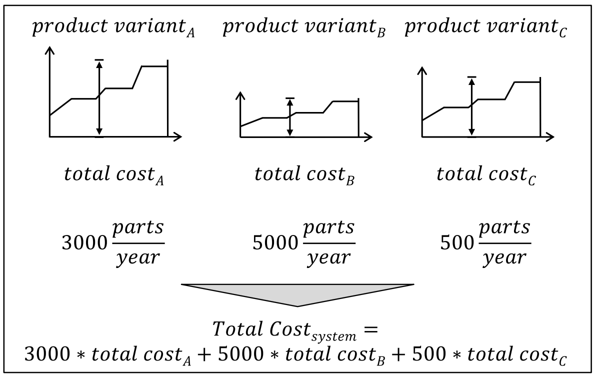


Figure 5: Calculation of a production system's total cost considering multiple product variants.

CTPs also provide the potential for the assessment of green practices. Criteria of green manufacturing, e.g., resource and energy consumption or (carbon) emissions (compare [24]), can be visualized either directly in separate green-time profiles (GTPs) that visualize the development of specific green parameters with respect to processing time or indirectly by specifying cost rates per green parameter and its monetary conversion, e.g., electricity cost can be derived from electricity consumption by specifying a cost rate of 0,124 €/kWh. The merge of lean and green parameters into a combined CTP provides the advantage of a single target dimension and is favored in this approach. Whereas separate lean and green profiles allow more in-depth assessment of the two criteria.

The resulting monetary savings per manufactured product variant *v* and assessed lean and green measure combination *c* compared to the production system's current status are considered as virtual revenues:

$$Revenues_{c,v} = Manufacturing\ Cost_{current\ status,v} - Manufacturing\ Cost_{c,v} \quad (2)$$

c:	lean/green measure combination
v:	product variant

The production system's overall virtual revenues of a lean and green combination *c* within a defined period of time *t* are determined by multiplying the revenues per product variant *v* with the respective quantity of manufactured parts and the subsequent summing up of all product variants' revenues:

$$Revenues_{c,t} = \sum_v quantity_{v,t} * Revenue_{c,v} \quad (3)$$

c: lean/green measure combination

v: product variant

t: time period

Besides periodical revenues, the assessment of a combinations' profitability depends on the comparison with necessary investments (one-time and periodically). The estimation of expenses for the implementation of a combination of lean and green measures is supported by enhanced accounting [25]. The structured assessment of expenses is achieved by providing standard assessment forms for each potential lean and green measure. Arising costs involve expenses for planning and realization, one-time investments in manufacturing equipment, as well as periodical expenses for the operation of the new lean and green configuration (Table 1).

Table 1: Enhanced accounting for the example of moderate reduction in setup time [23].

Enhanced accounting for a moderate reduction in setup time
Planning expenses (one-time investment): • planning staff • material expenses
Realization expenses (one-time investment): • project planning/control • project accompanying training measures • removal
Expenses in fixed assets (one-time investment): • manufacturing equipment
Expenses to operate the production system (periodical investment): • material expenses • project accompanying training measures

Thus, all required data for profitability assessment of the examined lean and green combinations are at hand. Periodical revenues are provided by the generated CTPs, necessary investments – both one-time and periodical – are made available by enhanced accounting. The net present value method is a straightforward procedure suitable for application in small and medium sized enterprises. Therefore, the profitability of an assessed lean and green combination is calculated as follows:

$$Net\ Present\ Value_{c,t} = -\sum(One\ Time\ Investments_c) + \sum_t \frac{Revenues_{c,t} - Periodical\ Expenditures_{c,t}}{(1 - IRR_c)^t} \quad (4)$$

c: lean/green measure combination

t: time period

IRR: Internal Rate of Return

The lean and green combination with the highest net present value promises greatest monetary benefit and should be implemented in the assessed production system. To determine the most beneficent implementation sequence of its lean and green measures, individual studies are conducted. Therefore, all measures contained in the targeted lean and green combination are assessed separately of one another in the analytical material flow model. The evaluation of the resulting performance indicators generates each measure's independent contribution to the monetary overall result of the targeted lean and green combination. The sorting of the individually assessed measures by monetary benefit results in the optimal implementation sequence - the production system's specific plan of measures.

4 SUMMARY AND OUTLOOK

The presented approach provides a methodology for the proactive monetary assessment of a production system's lean and green configuration and its target oriented further development. It is aiming at small and medium sized enterprises that request an affordable and easy to use planning methodology, which can be applied without extensive expertise in lean and green planning and without major investment in specialized planning software.

The presented methodology is a current research topic of the wbk Institute of Production Science, Karlsruhe and underlies ongoing further development. The tools applied during the approach will be merged into an integrated assessment environment to support the user as widely as possible with the application of the presented methodology. For in-depth programming tasks Visual Basic presents a suitable programming language. The thorough use of widely spread standard software ensures easy applicability of the developed tool in small and medium sized enterprises due to minor (if required at all) investments in software and software training. Additionally, the intended prototype in Excel® allows easy integration in existing IT-infrastructure. Thereby, small and medium sized enterprises have a comprehensive and well affordable assessment environment at hand to conduct the target oriented further development of their lean and green production system.

5 REFERENCES

[1] Bulard, M., et. al., 2012, Atlas der Globalisierung: die Welt von morgen, Le Monde Diplomatique/TAZ Verl.- und Vertriebs-GmbH, Berlin, Germany.

[2] Crude Oil and Commodity Prices, accessed: 17 Apr. 2013, available: http://www.oil-price.net/.

[3] TNS Infratest GmbH, 2011, Rohstoffe und Energie: Risiken umkämpfter Ressourcen, Commerzbank Mittelstandsbank, Frankfurt am Main, Germany.

[4] Detty, R.B., Yingling, J.C., 2000, Quantifying benefits of conversion to lean manufacturing with discrete event simulation: a case study, International Journal of Production Research, 38/2, pp. 429-445.

[5] Abdulmalek, F.A., Rajgopal, J., 2007, Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study, International Journal of Production Economics, 107, pp. 223-236.

[6] Tan, B., Gershwin, S.B., 2009, Analysis of a general Markovian two-stage continuous-flow production system with a finite buffer, International Journal of Production Economics, volume 120, issue 2, pp. 327-339.

[7] Lanza, G., Peters, S., 2012, Integrated capacity planning over highly volatile horizons, CIRP Annals – Manufacturing Technology, volume 61, issue 1, pp. 395-398.

[8] Diaz, N., Redelsheimer, E., Dornfeld, D., 2011, Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Ise, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 263-267, Braunschweig, Germany.

[9] Fang, K., Uhan, N., Zhao, F., Sutherland, J.W., 2011, A New Shop Scheduling Approach in Support of Sustainable Manufacturing, proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 305-310, Braunschweig, Germany.

[10] Diaz, N., Dornfeld, D., 2012, Cost and Energy Consumption Optimization of Product Manufacture in a Flexible Manufacturing System, Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, pp. 411-416, Berkeley, CA, USA.

[11] Hermann, C., Thiede, S., Stehr, J., Bergmann, L., 2008, An Environmental Perspective on Lean Production, Proceedings of the 41st CIRP Conference on Manufacturing Systems, pp. 83-88.

[12] Dombrowski, U., Herrmann, C., Lacker, T., Sonnentag, S., 2009, Modernisierung kleiner und mittlerer Unternehmen – ein ganzheitliches Konzept, Springer Verlag, Berlin, Heidelberg, Germany.

[13] Erlach, K., 1997, Wertstromdesign: Der Weg zur schlanken Fabrik, Springer Verlag, Berlin, Germany.

[14] Erlach, K., 2009, Energiewertstrom: Der Weg zur energieeffizienten Fabrik, Fraunhoferverlag, Stuttgart, Germany.

[15] 2000, VDI-3633: Simulation von Logistik-, Materialfluß- und Produktionssystemen – Grundlagen, VDI-Richtlinie, Blatt 1, VDI Verlag, Düsseldorf, Germany.

[16] Nightingdale, D., Mize, J., 2002, Development of a Lean Enterprise Transformation Maturity Model, Information-Knowledge Systems Management, 3, pp. 15-30.

[17] Christiansen, S., 2010, Methode zur Klassifikation und Entwicklung Reifegradbasierter Leistungsbewertungs- und Leistungssteigerungsmodelle, Dissertation, Universität Paderborn, Heinz Nixdorf Institut, Paderborn, Germany.

[18] Kneuper, R., 2003, CMMI – Verbesserung von Softwareprozessen mit Capability Maturity Model Integration, dpunkt.verlag, Heidelberg, Germany.

[19] Korge, A., Wagner, A., Weeber, M., 2011, HyPlan Handlungskatalog – Kurzbeschreibung der Methoden, accessed: 10 Apr. 2013, available: http://www.wbk.kit.edu/wbkintern/Forschung/Projekte/HyPlan/Ergebnisse/Download/index_d.php.

[20] Matzka, J., 2012, Discrete Time Analysis of Multi-Server Queuing Systems in Material Handling and Service, Wissenschaftliche Berichte des Insituts für Fördertechnik und Logistiksysteme des Karlsruher Instituts für Technologie, Band 75, Karlsruher Institut für Technologie (KIT), KIT Scientific Publishing, Karlsruhe, Germany.

[21] Hilton, R.W., 2008, Managerial Accounting: Creating Value in a Dynamic Business Environment, 8th edition, McGraw-Hill/Irwin, Boston, MA, USA.

[22] Rivera, L., 2006, Inter-Enterprise Cost-Time Profiling, Dissertation Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

[23] Lanza, G., Jondral, A., Book, J., 2011, Capability Assessment and Valuation of the Implementation of Lean Production Methods in Turbulent Environments, 4th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2011), Montreal, Canada.

[24] Dornfeld, D.A., 2013, Green Manufacturing – Fundamentals and Applications, Springer Science+Business Media, New York, USA.

[25] Brieke, M., Schulze, C., Schady, R., 2010, Erweiterte Wirtschaftlichkeitsrechnung (EWR) in der Fabrikplanung, VDI-ADB Fachausschuss (FA) Fabrikplanung – Arbeitsgruppe Erweiterte Wirtschaftlichkeitsrechnung.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

16.3 A study on a sustainability indicator of manufacturing processes

N. Mishima [1]

[1] Graduate School of Engineering and Resource Science, Akita University, Japan

Abstract

Since one of the most important goals of sustainable manufacturing is to obtain high quality manufacturing by low environmental impact, eco-efficiency of manufacturing processes can be the key indicator. In order to evaluate eco-efficiency, an evaluation method of manufacturing quality is indispensable. The author's former research group has proposed a new evaluation index for sustainability of products. The eco-efficiency type indicator was named Total Performance Indicator (TPI). This paper tries to apply TPI in evaluating energy efficiency of manufacturing processes, considering manufacturing quality. After showing a general procedure of calculation, the paper tries to calculate TPI in some case studies. Through the case studies, the paper shows the effectiveness of TPI in comparing a conventional process with an improved process. Finally, the paper concludes that the proposed index; TPI can be a powerful indicator in evaluating sustainability of manufacturing processes.

Keywords:

Sustainable Manufacturing; Manufacturing Processes, Eco-efficiency, Manufacturing Quality, Material Characteristics

1 INTRODUCTION

Since one of the most important goals of sustainable manufacturing is to obtain high quality manufacturing by low environmental impact, eco-efficiency [1-3] of manufacturing processes can be the key indicator. However, only by taking monetary value as the numerator like the original eco-efficiency, it is difficult to evaluate manufacturing quality. Qualities of manufacturing processes not always influence the price of the products directly. Plus, in B to B cases, intermediate prices are often decided by other reasons. On the other hand, for manufacturing engineers, qualities of manufacturing processes are the primary and the most important requirements. Indexes without considering manufacturing qualities cannot be suitable indexes in evaluating manufacturing processes. Thus, even for sustainable manufacturing, a certain method to quantify product qualities or manufacturing qualities is indispensable. Thus, the author's former research group has proposed [3] a new eco-efficiency type index and named it as Total Performance Indicator (TPI). TPI is an index which can validate the balance of product quality and environmental impact throughout the product lifecycle. In addition, cost is also an important factor in industrial processes, TPI take the cost as one of the factors in quantifying the index, Then the author have proposed a procedure to apply TPI not only for final products but also for intermediate products by taking manufacturing qualities into account [4]. And then, the procedure was applied to a few case studies [5,6]. In the former papers, the procedure to calculate TPI of manufacturing processes was shown by analysing an example. But, in this paper, the generalized procedure to evaluate manufacturing processes is discussed and shown. Then, the paper tries to conclude TPI is a suitable index in quantifying so-called eco-efficiencies of manufacturing processes.

2 GENERAL PROCEDURE TO CALCULATE TPI

2.1 Definition of manufacturing quality

In the former research [4], an index to evaluate a kind of an eco-efficiency of products was proposed. The index was named "Total Performance Indicator (TPI)" and the evaluation procedure using the index was named "Total Performance Analysis (TPA)," since the method can consider vlaue,environmental impact and cost totally. In order to evaluate real eco-efficiency of products, product's utility value, cost and environmental impact are considered simultaneously. In this context, user's value is defined as the weighed total of different functions of a product. The proposed index was the simplest combination of environmental and economical efficiencies. The difference of the TPA from normal eco-efficiency is that the method considers not only environmental impact but also economical aspects. TPA can also divide the products to components and can evaluate value creation efficiency of each component separately. Thus, it is possible to suggest which components are the bottlenecks in creating the value of the product efficiently. The next step of the study was to apply the same idea to evaluate the eco-efficiency of manufacturing processes [3]. Since the environmental, economical and quality aspects are the keys in manufacturing processes, the point is how to quantify qualities of manufacturing processes.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

Usually manufacturing processes are combinations of many segment processes. In addition, there are many ways to combine processes and boundary conditions. Therefore, it is very important to evaluate which manufacturing process is really eco-efficient comparing to alternative options. We define the total performance of the manufacturing process by (1). The equation expresses the balance of the product value created by the process, versus the cost and environmental impact necessary to fabricate the product. Then, (2) shows the simplified TPI of each segment process. The numerator 'Vi' of the equation may vary due to process quality. Manufacturing quality also has a strong relationship between cost and environmental impact of the process. We can quantify how efficient the target manufacturing process is, by calculating (2). After analyzing the manufacturing process and calculating the TPI of each segment process, it is possible to draw a TPI view graph. Segment processes with shallow slopes are suggested to be the primary targets of improvement. The image of analysis of segment processes and improvement are shown in Figure 1.

$$TPI_{process} = \frac{V}{\sum_{j=1}^{j=n} \sqrt{MCE_j \cdot MCC_j}} \tag{1}$$

TPIprocess: Total performance indicator

V: Total value of the process

MCCj: Cost of jh segment process,

n: Number of segment processes

MCEj: Environmental impact of jth segment process

$$TPI_{segment} = \frac{V_j}{\sqrt{MCE_j \cdot MCC_j}} \tag{2}$$

TPIsegment: Total performance indicator of the *j*th segment process

Vj: Value of the product added by *j*th segment process

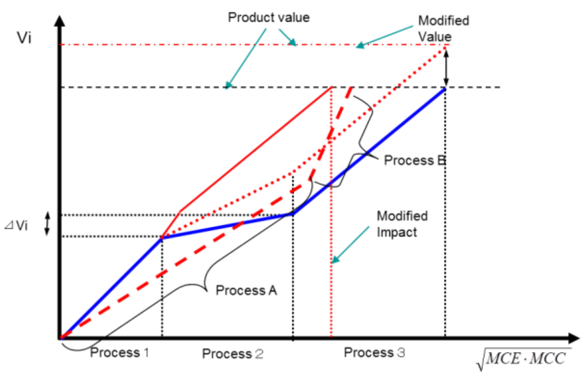


Figure 1: Concept of evaluating manufacturing processes

2.2 Requirements of manufacturing

Firstly, a general procedure to evaluate manufacturing processes by TPA should be discussed. The outcome of the manufacturing process is the product. Therefore, sum of values of segment manufacturing processes is equal to the value of the product. Usually, products have several functions. In the method, it is defined that the product value can be allocated values of different functions, based on the relative importance of the functions. Functions with importance are called Functional Requirements (FR) in the method. Applying QFD [7, 8], it is possible to clarify importance of each functional requirement of the product by using discrete score such as 9, 3, 1. Next (3) shows the calculation of the values of functional requirements.

$$FRV_i = V \cdot (u_i / T) \tag{3}$$

FRVi: value of ith functional requirement

V: value of the product

Ui: importance of *i*th FR based of QFD type scoring

T: sum of importance of all functional requirements

2.3 Quantifying values of quality characteristics

The second step of the analysis is to determine the contribution of each quality characteristic to the values of functional requirements. By identifying the relationship between functional requirements and quality characteristics using QFD again, value of each quality characteristic can be calculated by using (4). Table 1 shows the general idea to allocate values of functional requirements to quality characteristics, and (4) shows the general relations between values of FRs with values of quality characteristics.

$$QV_k = \sum_{i=1}^{n} FRV_i \cdot (w_{i,k} / T_i) \tag{4}$$

QVk: Value of *k*th quality characteristic

FRVi: Value of *i*th FR

wi,k: importance of *k*th quality characteristic on *i*th FR

Ti: sum of importance of all the related quality characteristics to *i*th FR

Table 1: Allocation of values to quality characteristics

		Functional requirements					
		Functional requirement 1	·	Functional requirement i	·	Functional requirement n	Value of quality characteristics (kJPY)
Value of FR (kJPY)		V_1		V_i		V_n	V
Quality characteristics	Quality characteristic 1	w_{11}		w_{i1}		w_{n1}	QV_1
	· · ·	· ·	·	· ·	·	· ·	
	Quality characteristic *k*	w_{1k}		w_{ik}		w_{nk}	QV_k
	· · ·	· ·	·	· ·	·	· ·	
	Quality characteristic *m*	w_{im}	·	w_{im}	·	w_{nm}	QV_m
	Sum	T_1	·	T_i	·	T_n	

2.4 Value of segment processes

The third step of the analysis is to know the contribution of each segment process on the value. By identifying the relation between each segment process composing the total manufacturing process and quality characteristics, it is possible to calculate value of segment processes. This calculation is shown in (5). Table 2 shows the value allocation based on (5). Again, the relational strengths between quality characteristics and segment processes will be determined, using the QFD type scoring based on engineers' technological knowledge.

$$PV_j = \sum_{k=1}^{m} QV_k \cdot (x_{j,k} / S_k) \qquad (5)$$

PV_j: Value of jth segment process
QV_k: Value of kth quality characteristic
$x_{j,k}$: relation strength between *k*th quality characteristic and *j*th segment process
S_k: sum of importance of related segment processes

Table 2: Allocation of values to segment processes

		Value of quality characteristics	Segment process 1	·	Segment process j	·	Segment process l
Quality characteristics	Quality characteristic 1	QV_1	x_{11}	·	x_{j1}	·	x_{l1}
	· · ·	· ·	· ·	·	· ·	·	· ·
	Quality characteristic k	QV_k	x_{k1}	·	x_{jk}	·	x_{lk}
	· · ·	· ·	· ·	·	· ·	·	· ·
	Quality characteristic m	QV_m	X_{1m}	·	x_{jm}	·	x_{lm}
	Value of the segment process (kJPY)		PV_1	·	PV_j	·	PV_l

3 TPI EVALUATION OF MANUFACTURING PROCESSES

3.1 Quantification of process quality

Through the procedure mentioned in the former section, values of quality characteristics are calculated in the second step of the analysis and values of segment processes are calculated in the third step of the analysis. Using these data, eco-efficiency of each segment process can be defined. Usually, eco-efficiencies of products or industrial sections are defined as (6) [3].On the other hand, our eco-efficiency type index; TPI of segment processes can be defined by (7).

$$Eco-efficency = \frac{Added\ Value}{Environmental\ impact} \qquad (6)$$

$$TPIp_j = \frac{PV_j}{\sqrt{E_j \times C_j}} \qquad (7)$$

$TPIp_j$: total performance indicator of the *j*th segment process
E_j: environmental impact of jth segment process
Cj: cost of the *j*th segment process

3.2 Quantification of the denominator

However, environmental impacts of manufacturing processes should not be considered separately, since environmental impacts caused by productions of manufacturing set-ups may occupy large parts of total environmental impacts. It is usual that improvements of manufacturing processes are realized along with improvements in manufacturing set-ups. In the analysis, environmental impacts of segment processes are evaluated through (8) taking environmental impacts of productions of manufacturing set-ups into account. In the equation, first 3 terms are those which can be considered as life cycle inventories in normal LCA procedures. The last term is what we are proposing in our method. As well as the environmental impact, costs of the process should be considered including all the costs caused by the manufacturing process. (9) shows the calculation of the cost.

$$E_j = (Ee_j + Ec_j + Ew_j) + Ep \times \frac{tp_j}{T \times L} \qquad (8)$$

Ee_j: environmental impact caused by energy consumption
Ec_j: environmental impact caused by consumables
Ew_j: environmental impact caused by waste treatment
Ep: environmental impact caused by the production of the total manufacturing set-up
tp_j: process time of *j*th process (hour)
T: total hour of operation per year (hour/year)
L: average lifetime of the production line (year)

$$C_j = (Ce_j + Cc_j + Cw_j) + Cp \times \frac{tp_j}{T \times L} \qquad (9)$$

Ce_j: cost of energy consumption
Cc_j: cost of consumables
Cw_j: cost of waste treatment
Cp: cost of the total production line

3.3 Quantification of process improvement

In evaluating manufacturing processes with eco-efficiency, absolute values of eco-efficiency have no significant meaning. Since usually, manufacturing processes are intermediate steps of production, value of the segment process may change due to business-to-business relations. Much more important thing is whether the process improvement has been carried out and whether the efficiency of manufacturing process has been enhanced. As it was mentioned in the beginning, the purpose of the procedure to evaluate quality characteristics is to find the target of improvement. Once the process is improved, it is also necessary to quantify the improvement and compare conventional processes with improved processes. Equation shown below expresses how the process improvement can be quantified. Plus, (11) shows the quantification of the improvement of the segment process.

$$QV_k' = QV_k \times \frac{P_k'}{P_k} \tag{10}$$

QVk': Value of improved *k*th quality characteristic
P_k: original performance index of *k*th quality characteristic
P_k': performance index of improved *k*th quality characteristic

$$PV_j' = \sum_{k=1}^{m} QV_k \cdot (x_{j,k} / S_k) \cdot \frac{P_k'}{P_k} \tag{11}$$

PV_j': value of improved *j*th segment process

4 APPLICATION TO A MANUFACTURING PROCESS

4.1 Series of processes

To show an actual procedure of evaluation process based on TPA, a practical example has been examined. As the target product we choose a ceramic heat radiation plate for power electric modules whose overview is shown in Figure 2. Ceramic radiation plates are used frequently because of its high thermal endurance, high specific strength and resistance ability to wear. Some of the authors have been engaging in process improvement of manufacturing process of ceramics. The functional requirements can be separated into 5 functional requirements (FR) such as 'heat radiation,' 'electric insulation capability,' and so on.

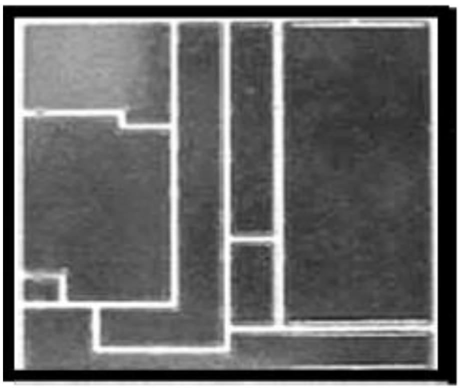


Figure 2: Exemplary product

4.2 Values of FRs and QCs

In this product, 5 FRs have the same importance on the product. Thus, the value of the product is equally distributed the values of quality characteristics. 5 FRs are related to 9 quality characteristics that are equivalent to material characteristics. The value of each FR is allocated to the value of each quality characteristics based on (4).

Table 3: Allocation of the value of heat radiation plate

		Functional requirements					
		Heat radiation capability	Hard-to-failure	Electric isolation capability	Smooth and parallel surface	Resistance capability against atmosphere	Value of quality characteristics (kJPY)
Value of FR (kJPY)		0.8	0.8	0.8	0.8	0.8	4.0
Quality characteristics of DPF	Heat conductivity	9					0.8
	Mechanical strength		9		1	1	0.44
	Fracture toughness		9		1	1	0.44
	Thermal expansion		3			1	0.17
	Electric resistance			9		1	0.46
	Dielectric breakdown strength			9		1	0.46
	Surface flatness				9		0.36
	Surface roughness				9		0.36
	Corrosion resistance					9	0.51
	Sum	9	21	18	20	14	

4.3 Values of segment processes

As it was shown in the general procedure, the next step is to allocate values of quality characteristics to the values of segment processes. In this case study, "Material supply," "Mixture," "Sheet forming," "Sintering," "Binder removal" and "Grinding." The value of each quality characteristic is allocated to the value of these 6 segment processes based on (5). Table 4 shows the result of the allocation.

Table 4: Allocation of the values of QCs

		Segment process						
		Value of quality characteristics	Material supply	Mixture	Sheet forming	Binder removal	Sintering	Grinding
Quality characteristics	Heat conductivity	0.8	9	3			3	
	Mechanical strength	0.44	3	3	1	3	9	
	Fracture toughness	0.44	3	3	1	3	9	
	Thermal expansion	0.17	9	3				
	Electric resistance	0.46	9	3		3	3	
	Dielectric breakdown strength	0.46	9	3		3	3	
	Surface flatness	0.36	1	3	9		1	
	Surface roughness	0.36	1	3			1	
	Corrosion resistance	0.51	9	1	1	1	3	
	Value of the segment process (kJPY)		1.80	0.67	0.16	0.34	0.89	0.34

4.4 Cost and environmental impact of the process

Table 5 shows the rough estimation of cost and environmental impact of the segment processes, based on the information from manufacturing engineers. These cost and environmental impact include those of machines. Each segment line indicates the value after the corresponding segment processes. An inclination of a segment line shows TPI of the corresponding segment process. An inclination of a virtual line connecting between the starting-point and the end-point of the lines indicates TPI of the total process.

Table 5: Rough estimation of environmental impact and cost

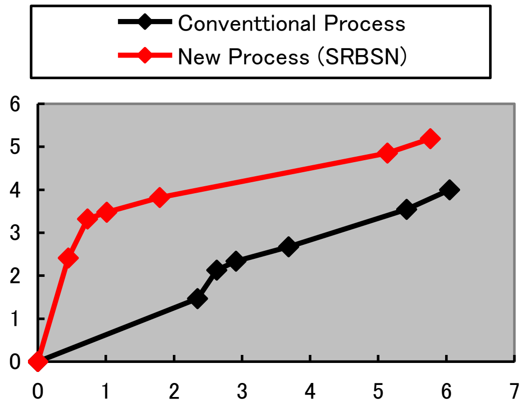
	Segment process						
	Material supply	Mixture	Sheet forming	Binder removal	Sintering	Grinding	Total
Value of the process (kJPY)	1.47	0.66	0.21	0.33	0.87	0.46	4
Environmental impact (kg-CO2/kg)	5	0.2	0.1	3	5	0.5	13.8
Cost (kJPY)	1.1	0.4	0.8	0.2	0.6	0.8	3.9

4.5 Improving the process

Improvement of silicon nitride manufacturing process is an ongoing research topic. Some methods to enhance the performance of the process or reduce the process time have been studied [9-13]. The purpose of using this process as an example is to ensure the design approach is to simulate the process improvement effect well. Therefore, it is necessary to compare with actual improvement and quantify the effect. The new material is called sintered reaction-bonded silicon nitride (SRBSN). In the new manufacturing process, more inexpensive silicon powder than silicon nitride powder is used. It results that the cost and the environmental impact of 'material supply' is reduced compared to the original process. Contrarily, those of the new 'sintering' process increase. In addition, it has been reported that heat conductivity, insulation resistance and dielectric breakdown strength of the product are improved comparing to the conventional process. By calculating the values of improved quality characteristics by (7), it is possible to assign new values to them. Then, the values of quality characteristics are allocated to values of new segment processes. Table 6 shows the value, cost and environmental impact of the improved processes. Figure 3 is the TPI graph of the improved processes reflecting Table 6.

Table 6: Value, cost and environmental impact of the improved process

	Segment process						
	Material supply	Mixture	Sheet forming	Binder removal	Sintering	Grinding	Total
Value of the new process (kJPY)	2.41	0.91	0.16	0.34	1.03	0.34	5.19
Env. impact (SRBSN) (kg-CO2/kg)	1	0.2	0.1	3	7	0.5	11.8
Cost (SRBSN) (kJPY/kg)	0.2	0.4	0.8	0.2	1.6	0.8	4.0



4.6 Discussion

The comparison of TPI suggests that the material composition is the most important consideration. The 'sintering' of the SRBSN seems worse than that of the old process. However, it is inseparable with the new 'material supply.' The figure suggests that the design of material composition and manufacturing processes are inseparable to design a totally eco-efficient process.

5 SUMMARY

In this paper, a new index to evaluate efficiency of manufacturing processes was proposed. The index which was named Total Performance Indicator (TPI) was first developed to evaluate efficiencies of products, in the aspect of value creation efficiency and applied to evaluate manufacturing processes for establishing sustainable production. The feature of the evaluation is to take the value of the manufacturing process as the numerator, and square root of the environmental impact and cost as the denominator. Firstly, the general procedure to evaluate manufacturing processes based on the proposed method was shown in the paper. Then, the evaluation method was applied to an example which is a manufacturing process of heat radiation plates made by silicon nitride. In the example, by implementing a new manufacturing technology, material characteristics are greatly improved. The efficiency index proposed in this paper can evaluate improvements in quality characteristics which cannot be evaluated by conventional eco-efficiency. The new process to fabricate silicon nitride is called reactive-sintering. And a more efficient sintering method called high speed reactive sintering was analyzed too. The analytical result suggested that the improvement of the manufacturing process and the material can be quantified by the proposing efficiency index. The evaluation result based on this index can correspond to the sustainability of the manufacturing process. In other words, the proposed method will be a good method to evaluate sustainable production.

As for the future work, it is necessary to examine whether the quantification procedure of the values of manufacturing processes based on the values of quality characteristics is reasonable enough.

6 REFERENCES

[1] DeSimone, L.; Popoff, F. (1997): Eco-Efficiency - the Business Link to Sustainable Development -. Cambridge, MA: MIT Press.

[2] Tahara, K.; Yamaguch, K.; Sagisaka, M.; Inaba, A. (2004): CO2 Efficiency: A New Evaluation Method of Companies' Environmental Performances, proc. of the 6th International Conference on EcoBalance, pp.269-270, Tsukuba, Japan.

[3] Park P.J., Tahara. K., Inaba A. (2007): Product quality-based eco-efficiency applied to digital cameras, Journal of Environmental Management, 83-2, pp.158-170.

[3] Kondoh S., Masui K., Hattori M.; Mishima N. and Matsumoto M. (2008): Total Performance Analysis of Product Life-cycle Considering the Deterioration and Obsolescence of Product Value: International Journal of Product Development, Vol.6, Nos.3/4, pp334-352.

[4] Kondoh S., Mishima. , Masui K., Kurita T. and Matsumoto M., Proposal of total Performance Analysis of Manufacturing Processes, Proceedings of Ecodesign 2007, Tokyo, Japan, Dec. 2007, C2-2-2F.

[5] Kondoh S., Mishima N., Hotta Y., Watari K. and Masui K. (2009): Total Performance Analysis of Manufacturing Processes:, International Journal of Automation Technology, Vol.3 No.1, . pp.56-62.

[6] Kondoh S., Hyuga H., Zhou Y., Mishima N. and Hirao K. (2010): Analysis of Eco-efficiency of Ceramics Manufacturing Processes for Silicon Nitride, Proceedings of 17th CIRP/LCE, 2010.5

[7] Akao K. (1990): Quality Function Deployment, Productivity Process:, MIT press, Cambrige, M.A.

[8] Kondoh S., Umeda Y. and Togawa Y. (2007): Development of redesign method of production system based on QFD: Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol. 1, No. 1, pp.181-192..

[9] Zhu X., Hayashi H., Zhou Y. and Hirao K.: Influence of Additive Composition on Thermal and Mechanical Properties of Si3N4 Ceramics, J. Mater. Res., 19[11] 3270-3278 (2004).

[10] Zhu X., Zhou Y., Hirao K. And Lences Z.: Processing and Thermal conductivity of Sintered Reaction-Bonded Silicon Nitride, J. Am. Ceram., 89[11] 3331-3339 (2006)

[11] Hyuga H., Yoshida K., Kondo N., Kita H., Sugai J., Okano H., Tsuchida J.: Nitridation enhancing effect of ZrO2 on silicon powder, Material Letters, 62 (2008) 3475-3477.

[12] Zhou Y., Zhu X., Hirao K. And Lences Z.: Sintered-Reaction Bonded Silicon Nitride with High Thermal Conductivity and High Strength, Int. J. of Appl. Ceram. Tech., 5 [2] 119-126 (2008).

[13] Hyuga H., Yoshida K., Kondo N., Kita H., Sugai J., Okano H., Tsuchida J.: Nitridation enhancing effect of ZrO2 on silicon powder, Material Letters, 62 (2008) 3475-3477.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

16.4 Sustainable development of socio-economic systems: a new approach to assess

V. Glinskiy, L. Serga, M. Khvan

Novosibirsk State University of Economics and Management, Russia

Abstract

The existing methods to assess sustainability have already revealed their major shortcomings: difficulties in obtaining information, aggregate estimates with different dimensions, and the choice of indicators weights. Here we suggest a new approach to measure sustainable development of socio-economic systems.

Our approach offers a comprehensive analysis of five blocks of equilibrium indicators (economic, social, environmental, institutional, innovation) by integrating average levels of stability Index. The mean resistance level is defined as an average of the normalized indicators for sustainable socio-economic systems and has a value between 0 and 1. This allows distinguishing three equal intervals, each corresponding to a particular type of sustainable socio-economic system: low, medium and high.

The method was efficiently tested on data from Russian regions and may be also applied to monitor the sustainability of other socio-economic system.

Keywords:

Sustainable Development, Stability Level, Typological Classification, Type of Stability

Relevance of research. One of the key aspects in formation of economic growth is the sustainable development of the state which assumes formation of the balanced system in all fields of person's activity. At all readiness of sustainable development problems there are still many controversial, unsolved questions, including a problem of its measurement and assessment. Therefore the development of effective measurement methods of sustainable development, which would allow estimating it qualitatively and quantitatively, has high scientific and practical value.

Measurement of sustainable development assumes the analysis of such components as economic, ecological, social, institutional and others. The assessment of components data demands accounting indicators having various dimensions. This situation caused an emergence of several methodological approaches to measure sustainable development. However due to the absence of one common methodological approach these techniques cannot be applied to the complex assessment of social and economic system. Thus, the relevance to develop an integrated approach to studying this phenomenon is obvious [1, 2].

The basic methodological approaches to analysis and assessment of sustainable development. Today the problem of measurement and assessment of sustainable development is designated as one of the leading problems as it assumes the solution of a wide range of tasks covering all spheres of human existence. The methodology of sustainable development measurement is at a formation stage [3].

More than 20 years (after UN Conference in Rio de Janeiro, 1992) the leading international organizations, research teams develop and offer various approaches to a quantitative assessment of stability. Own techniques of the assessment are developed by the following large organizations – the UN, OECD, the World Bank, the European Community and others.

There are two basic approaches to forming a technique of an assessment of sustainable development (Fig. 1).

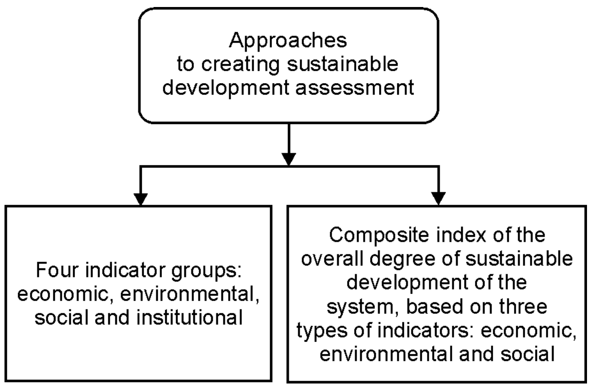


Figure 1: Approaches to formation a system of sustainable development ssessment.

Examples of the first approach are the following: "The purposes of the millennium development" the UN, methodology of the UN Commission on a sustainable development, the system of OECD indicators, ecological accounts of the European Community, indicators of load on the environment of statistical bureau of the European Union, "Indicators of world development" the World bank, "The guide to the reporting in the field of sustainable development" the UN on microlevel.

The methodology of the World Bank assumes calculating the "genuine savings" (GS) indicator:

$$GS = (GDS - CFC) + EDE – DPNR – DMGE, \quad (1)$$

where GDS – gross domestic savings,

CFC – consumption of fixed capital,

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

EDE – education domestic expenditure,

DPNR – depletion of natural resources,

DMGE – damages measurement of general environment. All the terms are expressed as percent of Gross National Income [4].

The second approach is presented by calculation of such integrated indicators of sustainable development as the aggregated indicators of the UN and the World Bank, an index of human development and an index of the adapted net savings, the integrated ecological indicators developed by the World Wide Fund for Nature (WWF) ("An ecological trace", an index of a live planet) [5].

The index of human development (IHD) takes into account level of socio-economic development of the society and includes 3 indicators: index of life expectancy: health and longevity measured by index of average life expectancy at birth; education index: access to education (average duration of education) and expected duration of education; gross national income index, showing level of economic development of the population [6]. These dimensions are standardized in numerical value from 0 to 1 geometric mean of which gives an IHD cumulated measure in the range from 0 to 1. Then the states are ranked on the base of this indicator.

Studying of existing approaches to assessment of stability level allowed revealing their main shortcomings: problem of obtaining information necessary for calculation of indicators; aggregation of the estimates having various dimensions; choice of indicators' scales, difficulty to compare received results for various social and economic systems [7, 8, 9, 10].

At the same time each approach has its advantages. The advantage of the first approach is usage of indicators' blocks, capable to estimate level of stability in different spheres of social activity. The advantage of application the aggregated indicator is a comfortable position with the development of management solutions as it allows drawing conclusions on stability (instability) of development and its dynamics.

Working out an assessment technique of stable development level of socio-economic system. Determining the level of social and economic sustainable development can be done on the base of integration of five equilibrium blocks: economic sphere, social sphere, environmental protection, innovation and institutional sphere. Each of these blocks has balanced influence as it shows an equal ranking impact on forming complex integral estimate of stability level. The integral estimate of socio-economic sustainable development is determined on the base of sustainable index level (Fig. 2).

Each block of indicators is formed on the basis of the indicators developed by the state statistics, and can include such well-known indicators, as the Gross Domestic Product (GDP) per capita (on the region it is possible to take the Gross Regional Product (GRP)); index of industrial production; unemployment rate; number of registered crimes on 100 thousand people; the number of doctors on 10 thousand people; emissions of polluting substances in atmospheric air; dumping the polluted sewage in superficial water objects; innovative activity of organizations; number of created advanced technologies; number of enterprises and organizations.

The choice of indicators to estimate sustainable development is made on the base of the following assumptions: availability

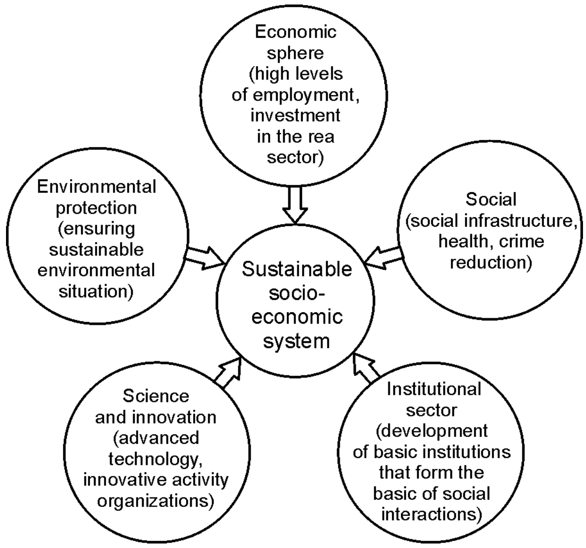


Figure 2: Scheme of sustainable development of social and economic system.

of information to determine the level of stability of the socio-economic system not only on macro-, but also on regional level; availability and openness of information required to calculate the integral estimate of the level of stability; an opportunity to estimate the level of stable development of the researched system in dynamics; the chosen indicators used for calculating the level of stability must exercise a significant influence on GRP which is confirmed by correlator-regression analysis.

The index of stability level ($\overline{ILS_i}$) is defined as an average value of indexes of separate blocks of indicators:

$$\overline{ILS_i} = \frac{\sum I_{ij}}{5}, \tag{2}$$

where I_{ij} – the index of the j – block of indicators on to i – social and economic system which pays off as average value of normalized indicators of this block:

$$I_{ij} = \frac{\sum P_{ij}^k}{n} \tag{3}$$

P_{ij}^k – normalized value of k – indicator to the j – block,

n – amount of indicators.

Normalized value of the indicators characterizing stability of social and economic systems, pays off on a formula:

$$P_{ij}^k = \frac{(X_{ij}^k - X_{\min j}^k)}{(X_{\max j}^k - X_{\min j}^k)} \tag{4}$$

or

$$P_{ij}^k = \frac{(X_{\max j}^k - X_{ij}^k)}{(X_{\max j}^k - X_{\min j}^k)} \tag{5}$$

where X_{ij}^k – value of k – indicator to the j – the block on to the i – social and economic system,

$X^{k}_{\max j}$ – the maximum value of *k* – indicator to the *j* – the block on to the *i* – social and economic system,

$X^{k}_{\min j}$ – the minimum value of *k* – indicator to the *j* – block to the *i* – social and economic system.

By calculation the Index of stability level it is necessary to consider the direction of each indicator's influence.By direct influence of the indicator (for example, GDP per capita) calculation is carried out by formula (4). If the indicator has the return influence (for example, unemployment rate), formula (5) is applied.

The offered level of stability Index accepts value from 0 to 1. It allows allocating three groups with equal intervals, each of which will correspond to a certain type of social and economic system stability: low, medium, high [11, 12, 13, 14, 15].

The following advantages of the level of stability Index can be pointed out: a) an opportunity to compare socio-ecenomic systems with each other not only in a specific period of time, but in dynamics as well, this allows receiving an entire view of developing each system; b) an opportunity to set specific fields of activity (blocks of indicators) and individual factors which hinder stability emergence.

This methodology allowes determining leaders and outsiders of socio-economic systems which gives a system with low stability level a chance to redirect its activity and work out constructive measures for development taking into consideration leader's experience.

Practical application of a technique of sustainable development level assessment on the example of subjects of the Russian Federation. On the basis of the Rosstat data [16] and the developed technique the levels of stability Index of federal districts of the Russian Federation were calculated and their typological classification was carried out. As a result the following distribution of federal districts according to their stability was received (tab. 1):

Table 1. Typology of federal districts of Russia in terms of sustainability in 2010

THE INDEX OF THE LEVEL OF SUSTAINABILITY	TYPE OF STABILITY	THE FEDERAL DISTRICT
0,000–0,333	low	North Caucasus, Southern
0,333–0,667	medium	North Western, Volga, Uralian, West Siberian, Far East
0,667–1,000	high	Central

In Russia the majority of federal districts (5 out of 8) take a position of "the average level of stability", here belong North Western, Volga, Uralian, West Siberian and Far East. The level of stability Index value for these regions is from 0,333 to 0,667. There is one leader – Central federal district (0,715) and one outsider – North Caucasus federal district (0,134). The Southern federal district takes an intermediate position between the low and the average level of stability. On 2010 the level of stability Index value for it was 0,301.

This picture can be seen during the whole analyzed decade and testifies the stable tendency of district's development (Fig. 3).

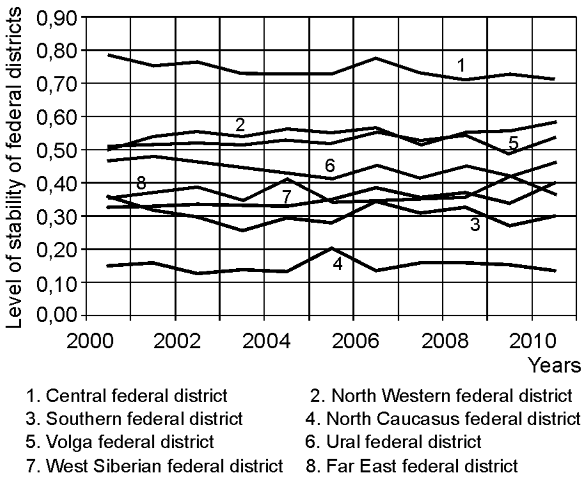


Figure 3: The schedule of dynamics of sustainable development of federal districts of Russia for 2000–2010.

The dynamics of changing the level of stability Index calculated for the federal districts in a period from 2000 to 2010 correspond to the typology received in 2010 for the regions given. Special attention should be payed to the Southern federal district because the level of stability Index values for this region is unstable, thus in 2002 its value was 0,296 (low type of stability), in 2006 – 0,344 (medium type of stability), in 2010 – 0,301 (low type of stability). That is this region has prospects for transition to the medium type of stability if actions corresponding this type are worked out and implemented.

Similar calculations were carried out for subjects of the Russian Federation in the federal districts, confirmed applicability of this indicator for the analysis of social and economic systems of other level of aggregation [17, 18, 19].

By means of the correlation analysis the interrelation between GRP and level of sustainable development was established. The linear correlation coefficient equal 0,931 testifies the existence of close, direct, linear dependence between these indicators. It proves the importance of assessment and monitoring of sustainable development of the region as a factor of growth of GRP, main source of development of the territory on short-term and medium-term prospect.

The offered technique of measurement level of sustainable development of social and economic systems is quite simple, it can be used at any levels of aggregation, it allows receiving rather informative integrated estimates and allows defining which of five spheres of societies activity (economic, social, ecological, science and innovations, institutional transformations) or what concrete indicator has a negative impact on the general level of stability of social and economic system.

The integrated approach to measurement level of stability gives the chance to receive complete idea of a condition of social and economic system, having defined its place in a group according to its stability, and to develop a program of actions directed on increase and stabilization of level of stability.

REFERENCES

[1] Kasimov, N.S., Mazurov, Yu.L. Tikunov, V.P., 2004, Concept of sustainable development: perception in Russia, Herald of the Russian Academy of Sciences, V. 74, 11: 28–36.

[2] 1989, Our common future. Report of the International commission on environment and development, Moscow, Progress.

[3] How to measure sustainable development? [An electronic resource] – URL: http://ecoreporter.ru/node/239.

[4] Indicators of sustainable development [An electronic resource] – URL: http://ekonom-priroda.ru/upravlenie-prirodopolzovaniem-na-predpriyatii/5-indikatory-ustojchivogo-razvitiya.html.

[5] Indicators and indexes of sustainable development. [An electronic resource] – URL: http://www.cosd.ru/index.php?option=com_content&view=article&id=13&Itemid=15.

[6] Index of human potential development [An electronic resource] – URL: http://gtmarket.ru/ratings/human-development-index/human-development-index-info.

[7] Ivanov, V.A. Methodological basis of sustainable dtvelopment of regional socio-eco-aconomic systems [An electronic resource] – URL: http://koet.syktsu.ru/vestnik/2011/2011-2/3/3.htm.

[8] Korchagina, Ye. V. Methods of estimation level of sustainable development of regional socio-economic systems // Questions of economic theory. Macroeconomics [An electronic resource] – URL: http://cyberleninka.ru/article/n/metody-otsenki-ustoychivogo-razvitiya-regionalnyh-sotsialno-ekonomicheskih-sistem.

[9] Uskova, T.V. Leading region's sustainable development [An electronic resource] – URL: http://library.vscc.ac.ru/Files/books/12997391861753V.PDF.

[10] Ursul, A.D., Romanovich, A.L. Concept of stable development and problem of safety [An electronic resource] – URL: http://filosof.historic.ru/books/item/f00/s00/z0000706/index.shtml

[11] Glinskiy, V.V., 2010, Methods of typology of the administrative tasks given in the decision, Applied statistics, Germany, LAP LAMBERT Academic Publishing GmbH&Co. KG, Saarbrucken, Germany.

[12] Glinskiy, V.V., Gusev, Yu.V., Zolotarenko, S.G., Serga, L.K., 2012, Portfolio analysis in typology of data: methodology and applications in support of administrative decisions, Vestnik NGUEU, 1: 25–53.

[13] Glinskiy, V.V., Ionin, V.G., 2002, Statistical analysis, Training Guide, Moscow, INFRA-M, Novosibirsk, Siberian Agreement.

[14] Serga, L.K., Nikiforova, M.I., Rumynskaya, Ye.S., Khvan, M.S., 2012, Applied use of methods of the portfolio analysis, Vestnik NGUEU, 3: 146–158.

[15] Serga, L.K., Khvan, M.S., 2012, Estimation of development stability of Federal districts on the base of typological grouping, Collected articles of V Russian national scientific and practical Internet-conference, Saratov, Saratovstat: 47–49.

[16] 2011, The Russian statistical year-book [An electronic resource] – URL: http://www.gks.ru/bgd/regl/b11_13/Main.htm.

[17] Khvan, M.S., 2012, Measuring the level of sustainable development of the Russian Federation regions, Collected articles of IX International practical conference for students, young scientists and business owners in economics, management and innovations, November, 2012, Tomsk, in 2 volumes, V. II, Tomsk, Publishing House of Tomsk Polytechnic University: 209–212.

[18] Khvan, M.S., 2013, Methodology of determination level of sustainable development of the Russian Federation regions, Reports' thesis of the 4th International scientific and practical conference for students "Statistical methods of economics and society analysis", May 14–16, 2013, Moscow, NRI "Higher School of Economics": 203–205.

[19] Khvan, M.S., Working out the strategy of economic growth on the base of attractivity assessment and competitiveness of Russian economics, Materials of the XI International scientific and practical conference "Actual economic problems and new ways of teaching (Smirnovsky readings)", May 16, 2012, St. Peterburg, in 3 volumes, V. 2, St. Petersburg, Publishing house MBI: 122.

11th Global Conference on Sustainable Manufacturing

2013
23rd - 25th September
Berlin - Germany

16.5 Developing a new assessment framework of sustainability in manufacturing enterprises

Ibrahim H. Garbie
Department of Mechanical and Industrial Engineering, Sultan Qaboos University, Muscat, Oman and Department of Mechanical Engineering at Helwan, Helwan University, Helwan, Cairo, Egypt

Abstract
Sustainability means the rearrangement of technological, scientific, economical, social and environmental resources. There are two levels of sustainability: Macro-Level (Global) such as Country and cities; and Micro-Level (Manufacturing enterprises) such as town and regional areas. In this paper, Micro-Level of sustainability will be targeted. The main objectives addressed in this paper are how to model the required issues/aspects, how to assess a new framework for measuring sustainability from indicators, aspects, dimensions, and integrating levels up to general sustainability. New concepts such as "economic-social, social-environmental, and environmental-economic sustainability" are also suggested and presented. The proposed framework is used in a hypothetical numerical example for investigate which dimensions are more significant in the sustainability. The results show that the estimation of sustainability performance is not simple task.
Keywords: Manufacturing enterprises; sustainability; sustainable development

1. INTRODUCTION

Sustainability or Sustainable development in manufacturing enterprises is defined as the way for improving the quality of life and well-being for the present and future generations [1-2]. Manufacturing enterprises are the backbone of modern industrialized society and they always have been considered as the cornerstone of the world's economy. Having a strong base of manufacturing is important to any advanced country because it stimulates all the other sectors of economy [3]. Sustainability of economy, society and environment has been recognized as priorities in manufacturing research [4] and it is considered a complex and an ill-structured problem. Sustainability is and will be a crucial issue for the present and future generations [1]. The design of sustainable manufacturing enterprises becomes the design for sustainability and sustainable development [5]. More recent conceptualizations of sustainability recognize the relationship among the three important principles: economic growth, social equity and respect for the environment [6-7]. Achieving sustainability in manufacturing enterprises requires a holistic spanning not just the manufactured products and the manufacturing processes involved in its fabrication but also the entire supply chain including the manufacturing systems across multiple product life-cycles [8-9]. In this paper, a new modeling and assessment framework of measuring sustainability in manufacturing enterprises will be explained and discussed.

2. LITERATURE REVIEW

Sustainability terms, definitions and interconnections for understanding and better communication in the process toward sustainable development were presented [10]. Sustainable engineering was recommended to be studied as a new educational course in Engineering Schools [11]. Sustainability information in the print press journals, periodicals and textbooks to provide the development of sustainability science was studied and analyzed [12]. Challenges, perspectives and recent advances in support of sustainable production operations decision-making through sustainable design, manufacture and supply chain management was reviewed [13]. The importance of integrating sustainability with manufacturing and along different objectives (function, competitiveness, profitability and productivity) was investigated [14] and the key requirements for engineering sustainability including sustainable resources, sustainable processes, increased efficiency and reduced environment impact was identified [15]. A brief explanation and an analysis of sixteen of the most widely initiatives to embed sustainability into companies' systems were provided [16].

Group reporting initiative (GRI) to evaluate the efficiency of sustainability performances in a group of Brazilian manufacturing companies focusing on measuring the inputs and outputs of processes only was used [17]. A new methodology of core and supplemental indicators for raising companies' awareness was suggested [18-19]. A five-step assessment procedure for sustainability was presented [20]. A framework for sustainable assessment was presented through the three dimensions of sustainability [21]. The performance of synthetic sustainable production indicators by adopting fuzzy measure and analytical network process (ANP) method was evaluated [22]. A methodology for designing manufacturing metrics was developed taken into consideration the specific concerns: availability factor and time remaining [23]. A framework to assess the sustainability of operations in the manufacturing sector was proposed [24-25]. Global reporting initiative (GRI) standard and methodology as a point of reference to analysis the reports of sustainability published by multinational organizations was used [26]. A framework for sustainability indicators as a tool for improvements was developed [27].

3. SUSTAINABILITY MODELING AND ASSESSMENT

The sustainability modeling is used to provide key information about vision of a manufacturing enterprise regarding assessment of economic, societal and environmental dimensions. Significant efforts have been made related to model and measure of sustainable manufacturing performance metrics. As consequences, achieving sustainability requires an integrated approach and multi-dimensional indicators that have to take into account all sustainability dimensions. An important facet of measuring and assessing sustainability and efforts to enhance it are

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

sustainability indicators. Indicators help to identify the status of something and the progress made towards an objective and the challenges. A challenge of estimating the sustainability of performance indicators is always in uncertainty parameter due to the rapid changes in economic situations, requirements of community and society, and environment data.

Also, the sustainable performance metrics have general characteristics representing into: easy to be measurable values (quantitatively and/or qualitatively), relevant and comprehensive, understandable and meaningful, manageable, reliable, cost effective, and timely manner [14]. A big challenge in selecting sustainable performance metrics is that it is not an inherently intuitive process [23]. Integrating two or more dimensions into one measure or performance to inter-relate different aspects of sustainability can be helpful for several reasons [5 and 27]. Firstly, integration reduces the number of performance measures, thus better facilitating decision-making process. Secondly, sustainability development is a holistic concept and ideally it should be considered in including all three dimensions simultaneously. Decision evaluation enables decision makers to perform scientific analysis: to weigh, score and rank the indicators and dimensions. Sustainability analysis has emerged as an important decision and to provide efficient and effective decision evaluation in all aspects of business [13].

In this paper, a relevant performance indicators and performance metrics are suggested. Also, a general framework to measure the sustainable performance metrics for dimension, integrating between dimensions, and general sustainability will be formulated and discussed.

3.1. Major Dimensions and issues Assessment

The mathematical model of the sustainable manufacturing enterprises either economic or social or environmental individually is presented in the following Equation (1).

$$I_K = \sum_{i=1}^{n_i} w_{i\_K}\, I_{i\_K} \tag{1}$$

Where: $I_K =$ sustainability of major dimension (e.g., economy (*E*) or society (*S*) or environment (*N*)), such as (I_E, I_S, I_N), I_E = sustainability index of economic dimension (*E*), I_S = sustainability index of social dimension (*S*), I_N = sustainability index of environmental dimension (*N*).

$n_i =$ Number of major issues or aspects in major dimension *K*.

The sustainability index of major issue/aspect *i* is calculated by using the following Equation (2).

$$I_{i-k} = \prod_{j=1}^{n_{ij}} (I_{ij})^{Y_{ij}} \tag{2}$$

Where: *j* = represents the aspects in each major issue of either economic or social or environmental sustainability model, $j = 1,2,...,n_{ij}$, $n_{ij} =$ number of indicators (performance metrics) in each major issue/aspect *i*, $I_{ij} =$ Performance metric of indicator *j* in major issue *i* representing ratio between towards the sustainability (*V*) and the existing (*U*). $I_{ij} = V_{ij}/U_{ij}$, $V_{ij} =$ Value of indicator *j* in major issue *i* towards the sustainability (*V*), $U_{ij} =$ Value of indicator *j* in major issue *i* regarding the existing (*U*), $Y_{ij} =$ Exponent of the change towards the sustainability (V) for indicator *j* in major issue *i* represents absolute value of change, $Y_{ij} = \log|v_{ij}|$, $v_{ij} =$ Value of the change towards sustainability (*V*) for indicator *j* in major issue *i*. Equation (2) is represented as an exponential power-sizing sustainable model after modification to be suitable to estimate the sustainability index for a single aspect including all indicators incorporating this issue.

3.2. Integrating sustainability

Social equity /economic-social sustainability

In order to estimate the social equity or so called "economic-social sustainability" (S_{ES}), the S_{ES} is formulated as the Equation (3).

$$S_{ES} = w_E^{\ *}(I_E) + w_S^{\ *}(I_S) \tag{3}$$

Where: S_{ES} = equity sustainability or economic-social sustainability assessment.

The $w_E^{\ *}$ *and* $w_S^{\ *}$ are the relative weights of the economic issues and social issues regarding economic-social sustainability (S_{ES}), respectively.

Bearable /social-environmental sustainability

Bearable sustainability is representing the interacting between social sustainability and environmental sustainability. This is so called (social-environmental sustainability". In order to estimate the bearable sustainability or social-environmental sustainability (S_{SN}), the S_{SN} is modeled as Equation (4).

$$S_{SN} = w_S^{\ **}(I_S) + w_N^{\ **}(I_N) \tag{4}$$

Where: S_{SN} = bearable sustainability or social-environmental sustainability assessment.

The $w_S^{\ **}$ *and* $w_N^{\ **}$ are the relative weights of the social issues and environmental issues regarding social-environmental sustainability (S_{SN}), respectively.

Viable /environmental-economic sustainability

The interaction between economy sustainability and environmental sustainability creates the new concept of sustainability which is so called "viable sustainability". The viable sustainability or environmental-economic sustainability (S_{NE})is clearly modeled as the Equation (5).

$$S_{NE} = w_N^{\ ***}(I_N) + w_E^{\ ***}(I_E) \tag{5}$$

Where: S_{NE} = viable sustainability or economic-environmental sustainability assessment of the manufacturing enterprise. The w_N^{***} *and* w_E^{***} are the relative weights of the environmental and economic issues regarding economic -environmental sustainability (S_{NE}), respectively.

3.3. General Sustainability

In order to estimate general sustainability assessment (*GS*) including the three dimensions of sustainability (economic (*E*), society (*S*), and Environmental (*N*)), the *GS* is clearly modeled as Equation (6) as a function of sustainability dimensions.

$$GS = f(E, S, N) \tag{6}$$

Equation (6) can be rewritten as the following Equations (7). Each term in Equation (7) represents a sub-sustainability of manufacturing enterprises or sustainability of each individual dimension. Adding these terms with relative weights is considered. These weights can be used as an existing reason to differentiate between major issues of sustainability. The sustainable model in Equation (7) is used to estimate the sustainability assessment *(GS*) of a manufacturing enterprise.

$$GS = w_E(I_E) + w_S(I_S) + w_N(I_N) \tag{7}$$

Where: *GS* = general sustainability assessment of the manufacturing enterprise. Note that G*S* may be equal to one or less than one or more than one. If G*S* equals one, then that indicates that there is exactly a doubling of the effort (time and cost) that is needed towards sustainability compared to the existing one. If the G*S* is more than one, there is more than double of the effort over the previous one. Also, if the G*S* is less than one, the sustainability will be decreased compared to doubling of effort and this is not usual [5].

The w_E, w_S *and* w_N are the relative weights of the economic, societal and environmental dimensions, respectively. In this paper, the relative weights are estimated using the Analytical Hierarchy Process (*AHP).* Figure 1 is used to illustrate the whole description and procedure to estimate the sustainability assessment for dimensions, integrating and general sustainability.

4. A HYPOTHETICAL NUMERICAL EXAMPLE

This numerical example is used to illustrate the proposed new assessment and modeling of sustainability regarding manufacturing enterprises. The XYZ Company is one of the leading extruders of aluminum profiles in the Gulf Countries Council (GCC). It located in the Sultanate of Oman. The sustainability assessment of each dimension is estimated using Equation (1) by estimating each major aspect using Equation (2) including all indicators in each aspect. The information required to illustrate these values is shown in Tables (1-3). The sustainability assessment of dimensions (economy, society and environment) are estimated and presented. With respect to economic dimension, the index of sustainability equals 3.55 and this value indicates that three times and half of the effort (time and cost) is required compared with existing sustainable industrial enterprise. This result means also that this enterprise urgently needs to sustainable its components. The sustainability index regarding social dimension equals almost 9.54 and this needs 9.54 times of the effort (time and cost) compared with present status to be survive. The sustainability assessment of environmental dimension is measured and estimated as 7.40. This value indicates that 7.40 times of the effort (time and cost) is required compared with present status. To estimate the economic-social sustainability, social-environmental sustainability, and environmental-economic sustainability, Equations (3-5) are used, respectively. The relative weights between each integrating were as follows: 0.67 and 0.33 for economic-social; 0.60 and 0.40 for social-environmental, and 0.25 and 0.75 for environmental-economic, respectively. The sustainability indexes for economic-social, social-environmental and environmental-economic were 5.53, 8.66, and 4.50, respectively. Regarding sustainability dimensions, the general sustainability index was estimated as a 7.0. It can be noticed that the social dimension has the largest percent (50%) following by environmental dimension (35%) and economical dimension (15%).

5. CONCLUSION, CONTRIBUTION AND RECOMMENDATIONS FOR FUTURE WORK

This paper presented and analyzed the sustainability performance metrics starting from individual dimensions until general sustainability index. Introducing the value of economic- social, social-environmental, and environmental-economic sustainability in manufacturing enterprises was investigated and estimated. It required emphasize on each dimension and its major issues/aspects. These major issues give manufacturing enterprises a tool to determine their actual (present) situation with respect to a sustainable manufacturing (future) and to set their goals. The relative weights between major aspects and between dimensions were proposed and estimated. The integrating sustainability index is modeled and assessed based on the three dimensions. This paper discussed the value of integrating sustainability index including each couple of them (economic- social; social-environmental; and environmental-economic sustainability). The economic sustainability is a very important to be firstly achieved to satisfy the social and environmental sustainability. Also, achieving economical sustainability without social sustainability and environmental sustainability is not usefulness. The requirements of achieving social sustainability and environmental sustainability are high and they need more effort and time to achieve them although they are ranked after economic sustainability.

The main contribution of this paper is presenting a framework for issues dimensions and general sustainability. Also, this framework is verification by using a construction computer software programming for all major issues, dimensions and general sustainable index. This framework is used for constructing the sustainable model and the sustainability value was estimated through the dynamic interaction between all dimensions and major issues (aspects) based on the perspective of manufacturing enterprise analysts and designers (author perspective). The author intends to valid the existing proposed sustainable framework and computer software to different industries sectors.

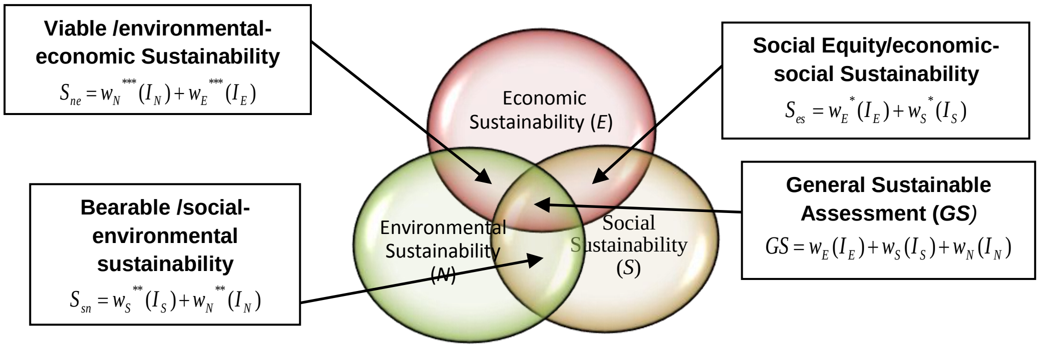


Figure 1: The interaction between dimensions of sustainability in Manufacturing Enterprises

Table 1: data related to economic dimension

Issue or aspect (*i*)	Indicator (*j*)	Units	Performance metrics	
			U_{ij}	V_{ij}
Globalization and international issues (*E1*)	Supply chain management	# of stops caused by supplier	4	1
	Information Technology	Degree or percentage (%) of using internet and e-commerce	80	90
	Energy Price	$/barrel	110	70
	Emerging markets	# of markets around the world	60	90
	Business models	# of new customers/year	4000	5000
Contemporary and contingency issues (*E2*)	Process technology	Degree or percentage (%) of using new technology	80	95
	Government regulations	Degree or percentage (%) of following the regulations	90	95
	Growth of populations	Number of populations increased per year per region	3000	1000
	Growth of economics	Degree or percentage (%) of profitability	70	95
	Consumption of resources	Percentage (%) of utilization of resources	80	95
Innovative designed products and research (*E3*)	Needs	Degree or percentage (%)	80	95
	Market opportunity	Degree or percentage (%)	80	90
	Product development cost	Percentage (%) of annual budget to R&D	2	5
	Product development time	Days, hours	25	5
	Development capability	Degree or percentage (%) of flexibility inside a plant	70	90
	Regionalized products	# of new regions related to total # of regions	3	10
	Personalized products	# of new products related to total # of products	5	10
Reconfigurable manufacturing Enterprises (*E4*)	Enterprise size	# of resources (e.g., machines)	85	75
	Enterprise functionality	# of different operations (flexibility range)	1700	2000
	Material handling equipments	# of material handling equipments	12	15
	Material handling storage	Space of storage (cubic meters)	400	600
	Identification system	# of new identification systems related to existing	1	3
	Plant location	# of locations of the plant around the world	3	7
	Plant layout (FL)	# of production departments	6	8
	Plant layout (PL)	Percentage (%) of modification in product layout	80	90
	Plant layout (CL)	# of focused cells	4	5
Manufacturing strategies (*E5*)	Complexity analysis	Degree or percentage (%) of complexity in the plant	80	70
	Lean production	Value added (e.g., employee productivity)	80	95
	Agile manufacturing	Degree or percentage (%) of agility	75	95
	Remanufacturing	# of parts or component can be replaced again/product	5	10
	Recycling processes	Percentage (%) of total consumption of recycled parts	50	95
	Product cost	$/unit	16	12

Performance evaluation (*E6*)	Response (lead time)	Days	11	8
	Enterprise productivity	Units/hour	20	30
	HR appraisal	Utilization (%) of manual labour	70	95
	Resources status	Reliability, overall equipment efficiency (OEE) (%)	80	95
	Product quality	Rate of customer complaints (units/unit time)	10	1
Flexible organization management (*E7*)	Strategic planning	Degree of clarity of strategic planning	70	95
	Organizing work	# of subordinates per supervisor	10	5
	Organization structure	# of organization structure	5	3
	Leadership role	Degree or percentage (%) of leadership	70	95
	Staffing	Percentage (%) to access to skilled personnel	30	80
	Managing culture	Percentage (%) of understanding foreign cultures	70	90

Table 2: data related to social dimension

Issue or aspect (*i*)	**Indicator (*j*)**	**Units**	**Performance metrics**	
			U_{ij}	V_{ij}
Work management (*S1*)	Employment	# of new employees per year	10	30
	Work conditions	# of accidents due to working condition	10	1
	Social dialogue	Degree or percentage (%) of talking between stakeholders	85	95
	Social security	Degree or percentage (%) of social security	80	95
	HR development	# of training hours/employee	10	30
Human rights (*S2*)	Child labour	Degree or percentage (%) of hiring children	5	1
	Freedom of association	Degree or percentage (%) of creating association	70	95
	Discrimination	Degree or percentage (%) of discrimination	30	2
Societal commitment (*S3*)	Involvement in local Community	Degree or percentage (%) of involvement in local community	75	95
	Education	Average of education level per total employees	50	60
	Healthcare	Degree or percentage (%) of health service level	70	85
	Job creation	# of new jobs creation/ local community	150	250
	Societal investment	Degree or percentage (%) of annual budget to investment in society	3	10
	Culture and technological development	Degree or percentage (%) of technology and culture regarding society	15	30
Customers issues (*S4*)	Marketing and information	Degree or percentage (%)	85	95
	Private life protection	Degree or percentage (%)	95	99
	Access to essential services	Degree or percentage (%)	85	95
Business practices (*S5*)	Fight against corruption	Degree or percentage (%) of corruption	20	5
	Fair-trading	Degree or percentage (%)	70	85

Table 3: data related to environmental dimension

Issue or aspect (*i*)	**Indicator (*j*)**	**Units**	**Performance metrics**	
			U_{ij}	V_{ij}
Environment management (*N1*)	Environmental budget	Monetary units (cost for EHS compliance)	1500	2500
	Environmental certification	Degree or percentage (%) follows the compliance ISO14001	60	95
	Environmental concerns and compliance	Degree or percentage (%) of environmental impact assessment	80	95
	Workers implications	# of environmental accidents per year	5	0.50
Use of resources (*N2*)	Renewable energy	Degree or percentage (%) of using renewable energy/total energy	5	15
	Recycled water	Degree or percentage (%) of using recycled water/total water consumption	20	50
	Recyclable wastes	Degree or percentage (%) of using recycled wastes/total wastes	50	50
Pollution (*N3*)	Air pollution	Kg of gasses (e.g., carbon dioxide emission in air)	30	5
	Water pollution	Kg of particles	50	5
	Land pollution	Kg and/or cubic meters of particles are needed to land-	50	15

		filled		
Dangerousness (*N4*)	Dangerous inputs	Kg and/or cubic meters of dangerous materials	15	5
	Dangerous output	Kg and/or cubic meters of dangerous materials	10	1
	Dangerous wastes	Kg and/or cubic meters of dangerous wastes	5	0.50
Natural environmental (*N5*)	Eco-system services	Percentage (%) of Level of carbon dioxide in the atmospheric	30	5
	Bio-diversity	Degree or percentage (%) of health of ecosystems	80	95
	Land use	Squared meters of land used for the plant	20000	10000
	Development of rural areas	Percentage (%) of annual budget to investment regarding rural areas	2	10

6. REFERENCES

[1] Garetti, M., Taisch, M., 2012, Sustainable Manufacturing: Trends and Research Challenges, *Production* Planning and Control, 23/2-3, 83-104.

[2] Agustiady, T., Badiru, A.B., 2013, Sustainability –Utilizing Lean Six sigma Techniques, CRC Press (p.18), Boca Raton, FL, USA.

[3] Koren, Y., 2010, The Global Manufacturing Revolution-Product-Process-Business Integration and Reconfigurable Systems, Wiley, Hoboken, NJ, USA.

[4] Bi, Z., (2011), "Revisiting System Paradigms from the Viewpoint of Manufacturing Sustainability", Sustainability, 3, 1323-1340.

[5] Garbie, I.H., 2013, DFSME: Design for Sustainable Manufacturing Enterprises (an Economic Viewpoint), International Journal of Production Research, 51/2, 479-503.

[6] Jenkins, H., Yakovleva, N., 2006, Corporate Social Responsibility in the Mining Industry: Exploring Trends in Social and Environmental Disclosure, Journal of Cleaner Production, 14, 271-284.

[7] Caniato, F., Caridi, M., Crippa, L., Moretto, A., 2012, Environmental Sustainability in Fashion Supply Chains: an Exploratory Case Based Research, International Journal of Production Economics, 135/2, 659-670.

[8] Jawahir, I.S., Badurdeen, F., 2009, Assessment of Product and Process Sustainability towards Developing Metrics for Sustainable Manufacturing. In proceedings of the (NIST) Workshop on Sustainable Manufacturing, Washington, USA, 2009.

[9] Jayal, A.D., Badurdeen, F., Dillon, O.W., Jawahir, I.S., 2010, Sustainable Manufacturing: Modeling and Optimization Challenges at the Product, Process and System Levels, CIRP Journal of Manufacturing Science and Technology, 2/3, 144-152.

[10] Glavic, P., Lukman, R., 2007, Review of Sustainability Terms and their Definitions, Journal of Cleaner Production, 15, 1875-1885.

[11] Davidson, C.I., Hendrickson, C.T., Matthews, H.S., Bridges, M.W., Allen, D.T., Murphy, C.F., Allenby, B.R., Crittenden, J.C., Austin, S., 2010, Preparing Future Engineers for Challenges of the 21st Century: Sustainable Engineering, Journal of Cleaner Production, 18/7, 698-701.

[12] Hasna, A.M., 2010, Sustainability Classifications in Engineering: Discipline and Approach, International Journal of Sustainable Engineering, 3/4, 258-276.

[13] Liu, S. Leat, M., Smith, M.H., 2011, State-of-the-Art Sustainability Analysis Methodologies for Efficient Decision Support in Green Production Operations, International Journal of Sustainable Engineering, 4/3, 236-250.

[14] Rosen, M.A., Kishawy, H.A., 2012, Sustainable Manufacturing and Design: Concepts, Practices and Needs, Sustainability, 4, 154-174.

[15] Rossen, M.A., 2012, Engineering Sustainability: a Technical Approach to Sustainability, Sustainability, 4, 2270-2292.

[16] Lozano, R., 2012, Towards better Embedding Sustainability into Companies' Systems: an Analysis of Voluntary Corporate Initiatives, Journal of Cleaner Production, 25, 14-26.

[17] Martins, R.A., Araujo, J.B., Ometto, A.R., 2011, Investigation on use Sustainability Performance Measures by Brazilian Manufacturing Companies, Proceedings of the 2011 Industrial Engineering Research Conference, Institute of Industrial Engineers, May 21-25, 2011, Reno, NV, USA, 1121-1129.

[18] Veleva, V., Hart, M., Greiner, T., Grumbley, C., 2001, Indictors of Sustainable Production, Journal of Cleaner Production, 9/5, 447-452.

[19] Veleva, V., Ellenbecker, M., 2001, Indicators of Sustainable Production: Framework and Methodology. Journal of Cleaner Production, 9/6, 519-549.

[20] Ron, A.J.d., 1998, Sustainable Production: the Ultimate Result of a Continuous Improvement, International Journal of Production Economics, 56-57, 99-110.

[21] Winroth, M. Almstrom, P., Andersson, C., 2012, Sustainable Indicators at Factory Level-a Framework for Practical Assessment, Proceedings of the 2012 Industrial and Systems Engineering Research Conference, May 18-23, 2012, New Orland, Florida, USA.

[22] Tseng, M.-L, Divinagracia, L., Divinagracia, R., 2009, Evaluating Firm's Sustainable Production Indicators in Uncertainty, Comp. and Ind. Eng., 57, 1393-1403.

[23] Weiser, C.R., Vijayaraghavan, A., Dornfeld, D., 2008, Metrics for Sustainable Manufacturing, Proceedings of the 2008 International Conference (MSEC2008), October 7-10, 2008, Evanston, Illinois, USA, 1-9.

[24] Labuschagne, C., Brent, A.C., Erck, R.P., 2005, Assessing the Sustainability Performances of Industries, Journal of Cleaner Production, 13, 373-385.

[25] Labuschagne , C., and Brent, A.C., 2008, An Industry Perspective of the Completeness and Relevance of a Social Assessment Framework for Project and Technology Management in the Manufacturing Sector, Journal of Cleaner Production, 19, 253-262.

[26] Leszczynska, A., 2012, Towards Shareholders' Value: an Analysis of Sustainability Reports, Industrial Management & Data Systems, 112/6, 911-928.

[27] Azapagic, A., 2004, Developing a Framework for Sustainable Development Indictors for the Mining and Minerals Industry, Journal of Cleaner Production, 12, 639-662.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

16.6 Achieving resource- and energy-efficient system optima for production chains using cognitive self-optimization

R. Schmitt[1,2], E. Permin[2*], S. Losse[1]

[1]Chair for Production Metrology and Quality Management, Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Steinbachstraße 19, 52074 Aachen, Germany

[2]Department for Production Quality and Metrology, Fraunhofer Institute for Production Technology (IPT), Steinbachstraße 17, 52074 Aachen, Germany

Abstract

Production systems no longer have to pursue one, but a set of goals. Classic optimization regarding lead time or capacity utilization is still sought after, but was extended by factors such as energy consumption or use of cooling lubricants. Thus the models of dependencies and system behavior become more complex, hampering optimization by classic algorithmic approaches.

One subdomain of the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" examines the potential of cognitive self-optimization as a way of handling technical complexity. This paper analyses the constraints and dependencies that have to be considered to find overall optima for process chains and gives an assumption of the associated complexity. This builds the base for future implementations of self-optimization to boost overall resource- and energy-efficiency in process chains. Furthermore, examples are presented on how optimization can be realized by using cognition and self-optimization.

Keywords:

Self-optimization of process chains, complexity of Job Shop Scheduling problems, production system optima

1 INTRODUCTION

The determination of optimal sequences of jobs that need to be conducted on a group of machines is called "Job Shop Scheduling" (JSP) and has been one of the classic optimization tasks in mathematical production research ever since [1]. The basic problem of JSP can be described as follows: For a specific group of components, all with individual subsequent production steps, an optimal overall sequence of conducting these on a specific group of machines, needs to be found. Usually, the overall production time ("makespan") is the optimization goal that is meant to be minimized. An example of a 3-machine 3-component problem, where each component has to be processed on each machine, but in differing sequences, is presented in figure 1.

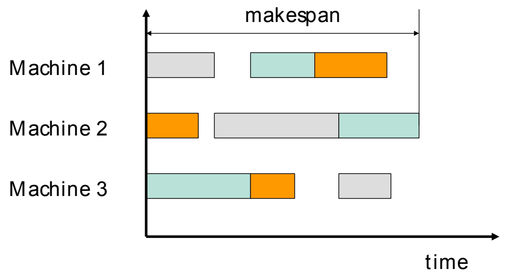


Figure 1: A basic job shop schedule

Every one of the nine jobs has a specific length, cutting down the problem to finding the optimal starting time for each job, determined by the completion of the previous job and the availability of the machine. Even though these problems often appear quite easy, the mathematical complexity connected with finding an optimal (or, at least, "good enough") order, rises exponentially. Hence, for problems including more than four to six machines and components, instead of systematically testing all possible sequences ("brute-force") regarding the desired objective (makespan, capacity usage etc.), other approaches have to be considered. As for the classic JSP discussed above, heuristics such as the nearest-neighborhood algorithm [2] or more advanced approaches such as artificial neural networks [3], agent-based-networks [4], genetic algorithms [2] or ant-colony-optimization [5] have been used successfully.

When considering more options for each job, e.g. the process velocity to influence energy consumption, the number of options (and thus the mathematical complexity) manifolds. Still, such variables need to be regarded to find overall optima for process chains. Therefore, this paper analyses the constraints and dependencies that have to be considered and gives an assumption of the associated complexity. Furthermore, examples are presented on how optimization can be realized by using cognition and self-optimization, which is one of the main topics of the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" in Aachen.

2 OPTIMIZATION GOALS FOR PRODUCTION SYSTEMS

Due to a study conducted in [6], the lifecycle cost of a machine tool is mainly composed of operating expenses, as the purchase price only makes up for 20% of the total. Furthermore, 40% of the operating expenses are caused by

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

the consumables electrical energy, coolant lubricants and pressurized air, as shown in fig. 2. As their consumption strongly depends on the process parameters, the consideration of machine variables in scheduling has an enormous influence on total costs of a process chain as well as its resource- and eco-efficiency.

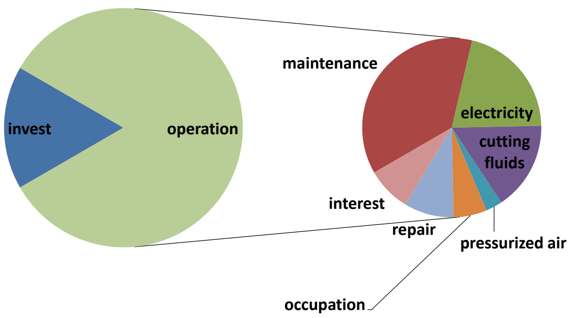


Figure 2: Lifecycle-cost for a tool machine [6]

Besides economic considerations, ecologic objectives can be included into the goal system of production processes [7]. The impact assessment and the evaluation of process inputs and outputs can be achieved by metrics such as the carbon footprint. Ecological assessments have been widely in use in certain industries with a high amount of resource consumption and pollution potential, e.g. energy production or the chemical industry. Several examples of the integration of LCA methods for production processes into multi-dimensional optimization approaches can be found in the scientific literature [8], [9].

Including single machine variables and behavior into Job Shop Scheduling indicates three major challenges: optima for single machines and complete process chains may differ, the determination of in- and outputs for each machine model need to be known and the complexity of the planning algorithm manifolds. Hence these issues are discussed in the following sections.

2.1 Optimization of single processes vs. process chains

For a single process, the economically and - most of the time also - ecologically optimum operating point for a single tool machine is the maximum operating speed. This is mainly due to the high amount of auxiliary units, e.g. pumps or electronics, which constantly consume electrical energy regardless of the machine being idle or running at full speed [10], [11]. For an entire process chain, priorities can differ: E.g. the electricity cost for industrial companies is normally determined by two major components: the total energy consumed, and the maximum load peak required. So instead of having several machines operating at maximum speed, it can be more cost-efficient to reduce process velocity when operating close to an energy peak load [12].

The same metric applies to the consumption of cooling fluids and tool lifetime for chipping operations such as milling or drilling. Most machines use closed cycles, so that fluids are not lost but filtered and re-used. Still, a large share is lost due to vaporization [13]. The need for cooling corresponds to the heat development at the tool cutting edge and thus the material removal rate. Reducing cutting speed where possible can minimize the need for cooling lubricants and extend the tool life. On the other hand, it increases the total energy consumption [10] and, if the decelerated process causes subsequent jobs to start later, deteriorates the overall process chain efficiency.

Thus, the optimum for single processes and complete process chains can differ, depending on the system boundaries and the applied metrics for the evaluation of an operating point.

2.2 Machine tool behavior and dependencies

The prediction of machine tools behavior e.g. regarding their energy consumption has been subject to various scientific projects and approaches (see [14], [15], [16] or [17]). Results show that these models are able to predict the machine behavior within very close limits and thus can contribute to realize process optimization. Fig. 3 illustrates some of the dependencies of the resource consumption and output parameters of a cutting machine from in-machine units and the input control variables. More important than the exact determination of each dependency is the insight that when starting to consider in- and output parameters for each job to determine e.g. the consumption of electrical energy, the original Job Shop Scheduling problem expands significantly.

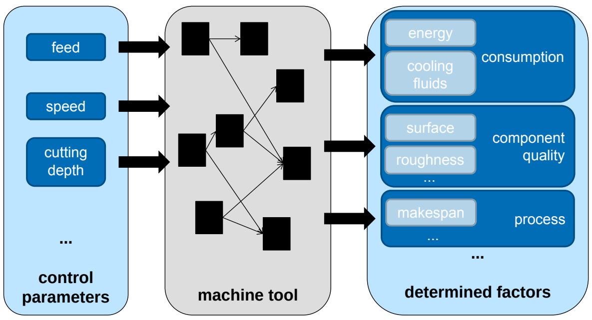


Figure 3:control parameters and dependend factors for a machine tool

For the basic scheduling problem, the sequence of jobs was the only focus, thus reducing the optimization to only one parameter per job – its position within the schedule. Considering machine behaviour models as presented above now leaves a whole set of options for each sequence. To evaluate the implied consequences for scheduling algorithms, the expanditure of the original problem is examined in the following section.

2.3 Complexity of the central planning approach

When looking at the intermediate units and interdependencies presented in the section above, it becomes clear that deterministically planning the control parameters for each machine even on a medium sized shop floor becomes more complex.

A classic job shop scheduling problem consisting of 10 machines and 10 components was introduced by [18] in 1967 and has since been a major benchmark for solving algorithms. In 2009, Schwindl [19] calculated the number of possible sequences for this problem to be $(10!)^{10}$ ($= 3.95 \times 10^{65}$), blocking the then known world's most powerful computer for several millions years if trying to solve if by a “brute force”-approach. Even though near-optimal sequences for this classic JSP-benchmark can be found within minutes using advanced approaches such as genetic algorithms, it becomes clear that the complexity quickly manifolds with the number of machines, components or other options.

When considering machine parameters, the number of possible set-ups for each sequence rises. As discussed above, a machine tool has several input parameters (m), each of which has several values (n). To reduce the number of options, the input parameters are regarded as discrete values, e.g. low-medium-high, or 1-5. So for a job shop scheduling problem with k machines and l components, the number of possible set-ups for each sequence adds up to:

$$(n^m)^{k\times l} = n^{\,m\times k\times l}$$

Taking the benchmark problem into account (10 machines and 10 components, adding up to 100 single jobs) and assuming machines with three parameters (e.g. feed, speed and cutting depth), each with only three values (low – medium – high), this ends up to $1{,}37\text{x}10^{143}$ possible set-ups for each sequence. As shown by [19], there are $3{,}95 \text{ x } 10^{65}$ possible sequences for this standard JSP-benchmark.

As discussed in section 2.1, most processes will normally be conducted at the maximum possible rate and reduced only when necessary. Still, as the number of machine parameters can be higher and discretization will normally be conducted in much finer steps than three, complexity can be said to be beyond the reasonable application of “brute force”-approaches. Hence more advanced approaches to realize the inclusion of machine parameters and models into Job Shop Scheduling are discussed in the following section.

3 APPROACHES TO INCLUDE RESOURCE CONSUMPTION INTO JOB SHOP SCHEDULING

First approaches to include the resource consumption of tool machine into Job Shop Scheduling can be found in [20], [21] and [22]. As the complexity of the induced mathematical problems rises [21], more advanced approaches such as combined local search algorithms [22] or ant-colony-optimization [23] are applied to find more optimal solutions.

To overcome the complexity problem when combining Job Shop Scheduling and resource consumption as described above, distributed decision making with agent-based algorithms [24] and self-optimization appear to be two promising approaches. In the following section, these are examined more closely.

3.1 Agent-based distributed decision making

When handling job shop problems with a high complexity, one promising approach is the development of distributed, agent-based networks [4]. A good introduction to this topic can be found in [25] and [26]. First attempts of distributed, agent-based decision-making go back to the 1980s [27]. The number of its successful applications has since multiplied, a good overview can be found in [28] and [29]. Advantages of the distributed, agent-based network approach are its robustness and the ability to find near optimal solutions even for complex problems within an acceptable calculation time [30]. The emergence of cyber-physical systems in the scientific spotlight underlines the future role of this approach, as CPS mainly resemble distributed networks of interacting and communicating machines [31].

Another advantage of distributed networks is the possibility to add and withdraw subsystems (e.g. single machine tools) dynamically, e.g. in case of a technical failure. So when a single machine within a cooperating network breaks down, the remaining production system can continue without rearrangement of the control structure. This, of course, requires the existence of standardized communication protocols. Furthermore, agents in distributed networks can be equipped with the ability to learn, thus react to changed boundary conditions and system statuses. Learning is always conducted by comparing the achievement of an action and its intended goal. Thus, the goal needs to be known and quantifiable.

3.2 Self-optimizing process chains

Self-optimizing process chains resemble another promising approach to overcome the complexity problems discussed above. A good introduction to the concept of self-optimization as a way of setting up the control structure of more autonomous machines can be found in [32]. Basically, it resembles a procedure of three major steps:

i. analysis of the current system situation,
ii. determination of (new) system objectives and
iii. adaptation of the system’s behavior to the new surrounding conditions [33].

System objectives can either resemble single physical units such as vibration [34] or a specific torque [35] or multi-dimensional goals, e.g. a combination of the handling characteristics of a systems and its energy consumption, requiring multi-objective decision making and optimization [36].

The concept of self-optimization has been applied successfully to the control of demonstrator objects such as trains and robots [32] as well as real production processes such as laser resonator alignment [33], laser cutting or weaving [37].

Self-optimization can be used on various levels: on the level of a single machine, it can be applied to influence its parameters to achieve a local process optimum, as in the examples discussed above. On a shop floor or even factory level, the concept of self-optimization can help to reduce planning efforts and complexity by offering the option of cascading control loops [38], [39]. Instead of taking all decisions on one level, e.g. the factory control, goal vectors are used as a way of communicating between the different control loops, as presented in figure 4: On a factory level, certain jobs, boundary conditions and goals are assigned to a process chain. Here, these are enhanced with further information and split to be assigned to different machines. The tool machine will thus be allowed to optimize itself within its constraints and boundary conditions to achieve its assigned goals as good as possible. This way of arranging self-optimization on different levels within the factory infrastructure resembles the approach of cascading quality control loops as can be found in [40] and [41].

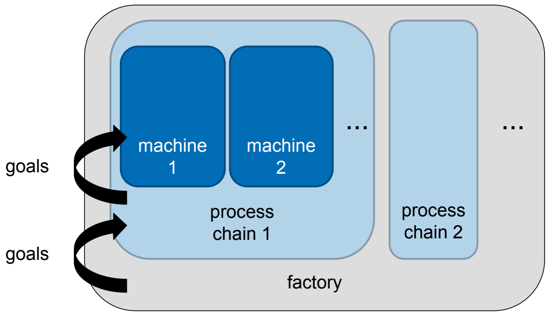


Figure 4: schematic diagram of cascading, self-optimizing control loops

An example of a goal vectors could be a specific job with the additional constraint not to exceed a certain peak load, total energy and lubrication consumption as well as a latest time of job completion.

4 NEED FOR FUTURE SCIENTIFIC WORK

As discussed above, distributed, agent-based decision making and self-optimizing process chain optimization can be a successful way of overcoming the induced complexity of a job shop scheduling problem that is expanded by modifiable machine parameters and thus contribute to achieve more global process chain optima.

Implementing these approaches causes two major demands that will thus be subject to further scientific work within the Cluster of Excellence: a well-known and quantifiable goal system and structures and protocols for inter-machine-communication.

4.1 Multi-dimensional goal systems

The major requirement for any kind of optimization algorithm is a known and quantifiable goal. To achieve a general optimum for a process chain, a larger group of goals needs to be considered. In addition to the makespan, that typically formed the optimization parameter for classic scheduling approaches, other process characteristics as e.g. resource consumption of electricity or cooling fluids have to be taken into account. Alongside a costing approach, these can also be evaluated in other metrics, e.g. reflecting ecological considerations. Thus, goals with differing physical units and scales would have to be compared to one another. Representing all of these goals in a quantifiable way requires the use of a multidimensional goal system that can be interpreted and used by a computer-based system or network. One major focus of the future scientific work thus needs to be the development of a complex goal system that represents economic, ecologic and socio-economic goals, resembling the three major perspectives (and thus assessments) that are taken into account when evaluating processes or products. A goal system has to enable trade-offs between the different performance measures and goals indicated by those assessments in a quantifiable way to support multi-dimensional decision making and optimization.

4.2 Communication networks and protocols

As discussed above, the application of self-optimizing process chains and distributed, agent-based production networks manifold the need for inter-machine communication. Different machines, factory and administration levels and networks have to exchange information and communicate goals and restrictions to enable cooperation. Thus, one focus of future scientific work will be to research effective communication networks and protocols to enable information exchange between single machines as well as superior planning and administration systems.

5 CONCLUSION

Production systems no longer have to pursue one, but a set of goals. Classic optimization regarding lead time or capacity utilization is still sought after, but needs to be extended by factors such as energy consumption or use of cooling lubricants to achieve overall system optima. Thus the models of interconnections and system dependencies of single machines and machine networks become more complex, hampering optimization by classic algorithmic approaches. Promising approaches to overcome the induced complexity, such as distributed agent-based networks and self-optimization, exist. Finding ways to enable inter-system-communication and developing goal systems for the evaluation of overall system optima are two major issues that will be taken into the focus of future scientific work.

6 ACKNOWLEDGMENTS

The authors would like to thank the German Research Foundation DFG for the kind support within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries".

7 REFERENCES

[1] P. Brucker, Scheduling. Wiesbaden: Akademischer Verlag, 1981.

[2] A. Henning, “Praktische Job-Shop-Scheduling-Probleme,” Universität Jena, Jena.

[3] D. J. Fonseca and D. Navaresse, “Artificial neural networks for job shop simulation,” Advanced Engineering Informatics, vol. 16, no. 4, pp. 241–246, 2002.

[4] H. W. Chun and R. Y. M. Wong, “N* - an agent-based negotiation algorithm for dynamic scheduling and rescheduling,” Advanced Engineering Informatics, vol. 17, no. 1, pp. 1–22, 2003.

[5] J. E. Bell and P. R. McMullen, “Ant colony optimization techniques for the vehicle routing problem,” Advanced Engineering Informatics, vol. 18, no. 1, pp. 41–48, 2004.

[6] K. Mattes, Wirtschaftlichkeitsbewertung: Bewertung der wirtschaftlichen Potenziale von energieeffizienten Anlagen und Maschinen, 2011.

[7] P. T. Mativenga and M. F. Rajemi, “Calculation of optimum cutting parameters based on minimum energy footprint,” CIRP Annals - Manufacturing Technology, vol. 60, no. 1, pp. 149–152, 2011.

[8] L. Gerber, M. Gassner, and F. Maréchal, “Systematic integration of LCA in process systems design: Application to combined fuel and electricity production from lignocellulosic biomass,” Computers & Chemical Engineering, vol. 35, no. 7, pp. 1265–1280, 2011.

[9] A. Dietz, C. Azzaro-Pantel, L. Pibouleau, and S. Domenech, “Multiobjective optimization for multiproduct batch plant design under economic and environmental considerations,” Computers & Chemical Engineering, vol. 30, no. 4, pp. 599–613, 2006.

[10] N. Diaz, M. Helu, A. Jarvis, S. Tönissen, D. Dornfeld, and R. Schlosser, “Strategies for Minimum Energy Operation for Precision Machining,” in The Proceedings of MTTRF 2009 Annual Meeting, pp. 1–5.

[11] N. Diaz, E. Redelsheimer, and D. Dornfeld, Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use. Green Manufacturing and Sustainable Manufacturing Partnership, Laboratory for Manufacturing and Sustainability, UC Berkeley, 2011.

[12] E. Müller, Energieeffiziente Fabriken planen und betreiben, Berlin: Springer, 2009.

[13] J. Dahmus, “An enviromental analysis of machining,” in Proceedings of IMECE, Anaheim, California, USA, November 13-19, 2004.

[14] S. Kara and W. Li, “Unit process energy consumption models for material removal processes,” CIRP Annals - Manufacturing Technology, vol. 60, no. 1, pp. 37–40, 2011.

[15] E. Abele, C. Eisele, and S. Schrems, “Simulation of the Energy Consumption of Machine Tools for a Specific Production Task,” in Leveraging Technology for a Sustainable World: Proceedings of the 19th Cirp Conference on Life Cycle Engineering, University of California at Berkeley, Berkeley, USA, May 23 - 25, 2012, D. A. Dornfeld and B. S. Linke, Eds.: Springer Verlag, 2012, pp. 233–237.

[16] S. T. Newman, A. Nassehi, R. Imani-Asrai, and V. Dhokia, “Energy efficient process planning for CNC machining,” CIRP Journal of Manufacturing Science and Technology, vol. 5, no. 2, pp. 127–136, http://www.sciencedirect.com/science/article/pii/S1755581712000223, 2012.

[17] C. Eisele, S. Schrems, and E. Abele, “Energy-Efficient Machine Tools through Simulation in the Design Process,” in Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011, J. Hesselbach, Ed, Berlin: Springer, 2011, pp. 258–262.

[18] G.L. Thompson, Ed, Industrial scheduling. Englewood Cliffs, N.J.: Prentice-Hall, 1963.

[19] K. Schwindl, Abbruchkriterien für Markovsche Optimierungsverfahren im Rahmen der Ablaufplanung. Berlin: Logos-Verl, 2009.

[20] A. Pechmann and I. Schöler, “Optimizing Energy Costs by Intelligent Production Scheduling: Glocalized Solutions for Sustainability in Manufacturing,” in Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011, J. Hesselbach, Ed, Berlin: Springer, 2011, pp. 293–298.

[21] K. Fang, N. Uhan, F. Zhao, and J. W. Sutherland, “A New Shop Scheduling Approach in Support of Sustainable Manufacturing,” in Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011, J. Hesselbach, Ed, Berlin: Springer, 2011, pp. 305–310.

[22] A. A. G. Bruzzone, D. Anghinolfi, M. Paolucci, and F. Tonelli, “Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops,” CIRP Annals - Manufacturing Technology, vol. 61, no. 1, pp. 459–462, 2012.

[23] H. Luo, B. Du, G. Q. Huang, H. Chen, and X. Li, “Hybrid flow shop scheduling considering machine electricity consumption cost,” International Journal of Production Economics, no. 0.

[24] Y.-C. Chou, H. Cao, and H. H. Cheng, “A bio-inspired mobile agent-based integrated system for flexible autonomic job shop scheduling,” Journal of Manufacturing Systems, no. 0.

[25] L. Monostori, J. Váncza, and S. R. T. Kumara, “Agent-Based Systems for Manufacturing,” CIRP Annals - Manufacturing Technology, vol. 55, no. 2, pp. 697–720, 2006.

[26] N. Jennings and M. J. Wooldridge, Agent technology: Foundations, applications, and markets. Berlin: Springer, 1998.

[27] H. van Dyke Parunak, “Manufacturing Experience with the Contract Net,” in Distributed Artificial Intelligence, pp. 285–310.

[28] P. Leitão, “Agent-based distributed manufacturing control: A state-of-the-art survey,” Distributed Control of Production Systems, vol. 22, no. 7, pp. 979–991, 2009.

[29] V. Hajarnavis, Intelligent agents in manufacturing automation (EN). In: Autonomous Agents in Control, 2005. The IEE Seminar on, Coventry, UK, 2005

[30] D. Trentesaux, P. Pesin, and C. Tahon, “Comparison of constraint logic programming and distributed problem solving: a case study for interactive, efficient and practicable job-shop scheduling,” Computers & Industrial Engineering, vol. 39, no. 1–2, pp. 187–211,

[31] E. Geisberger and M. Broy, Agenda CPS: Integrierte Forschungsagenda Cyber-Physical Systems.

[32] J. Gausemeier et al.: Selbstoptimierende Systeme des Maschinenbaus. Definitionen, Anwendungen, Konzepte. Paderborn, 2009.

[33] C. Brecher et al.: Self-optimizing approach for automated laser resonator alignment. In: Optics and Lasers in Engineering 50, pp. 287–292, 2009.

[34] R. Schmitt et al.: Integrative, selbstoptimierende Prozessketten. In: C. Brecher et al.: Integrative Produktionstechnik für Hochlohnländer. Springer, Berlin, pp. 1119-1131, 2011.

[35] R. Schmitt, M. Isermann, C. Wagels: Production Optimization by Cognitive Controlling Systems. In: International Conference on Competitive Manufacturing (COMA), Stellenbosch, South Africa, 3-5 February 2010

[36] R. Timmermann et al.: Optimale Umschaltstrategien bei Aktorausfall mit Pfadverfolgungstechniken. In: J. Gausemeier: Entwurf mechatronischer Systeme. Wissenschaftsforum 2013 Intelligente Technische Systeme, Paderborn, 2013, pp. 191-203

[37] U. Thombansen et al.: der Weg zu Selbstoptimierenden Fertigungstechnologien. In: C. Brecher et al.: Integrative Produktionstechnik für Hochlohnländer. Springer, Berlin, pp. 849-908, 2011.

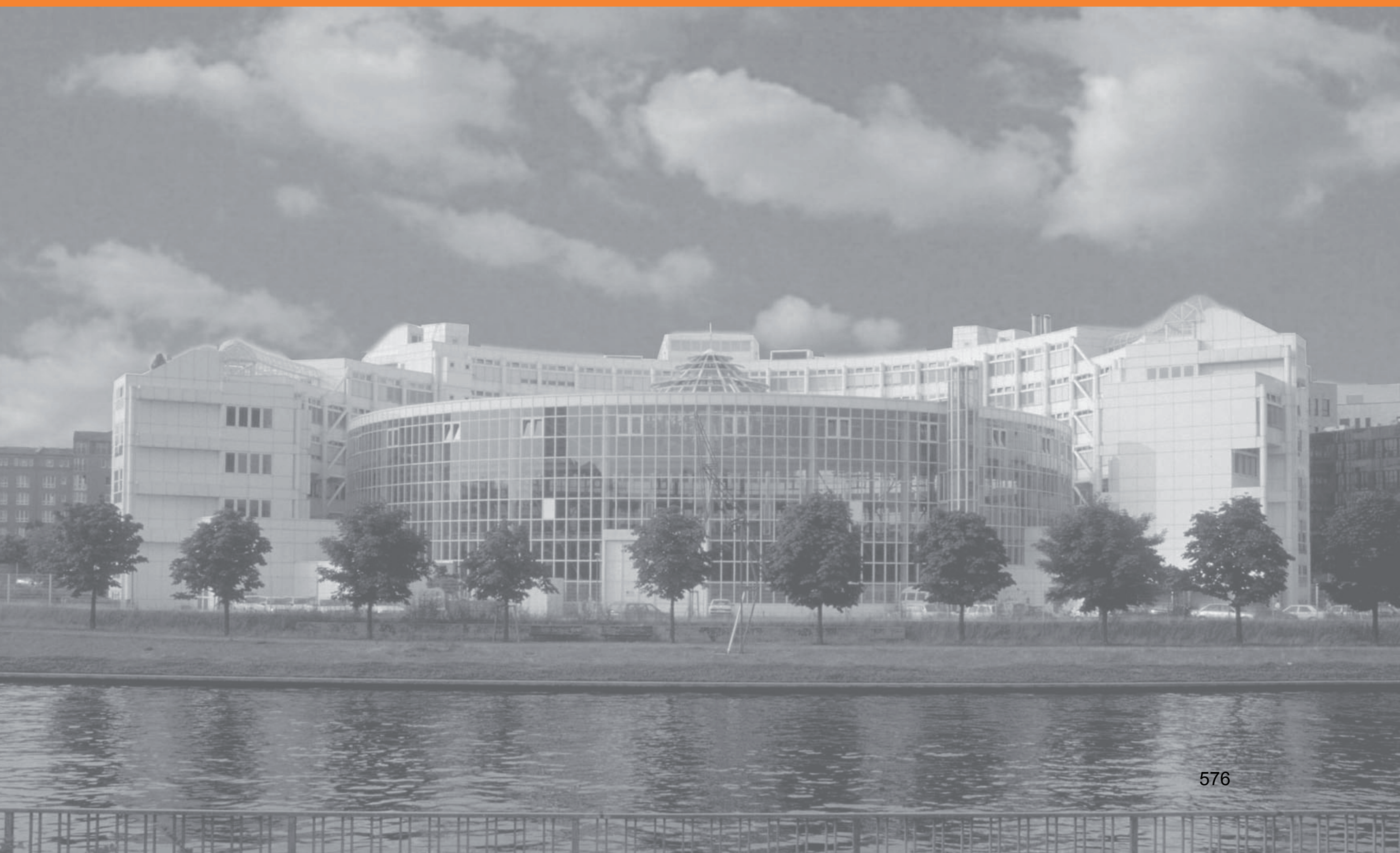
[38] G. Schuh et al.: High resolution supply chain management: optimized processes based on self-optimizing control loops and real time data. In: Production Engineering Research and Development. 5, pp. 433–442, 2011.

[39] R. Schmitt et al.: Integrative Produktion von Hinterachsgetrieben für PKW. In: In: C. Brecher et al.: Integrative Produktionstechnik für Hochlohnländer. Springer, Berlin, pp. 1119-1131, 2011.

[40] R. Schmitt et al.: Design and assessment of quality control loops for stable business processes. In: CIRP Annals of Manufacturing Technology, Nr. 61 (2012), pp. 439–444

[41] R. Schmitt; T. Pfeifer: Qualitätsmanagement. Hanser, München, 2010.

Session 17
Strategies



GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

17.1 What do we assess for a sustainable society from a manufacturing perspective?

K. Wolf[1], Y.-J. Chang[1], R. Scheumann[1], S. Neugebauer[1], A. Lehmann[1], M. Finkbeiner[1]
[1] Department of Environmental Technology, Technische Universität Berlin, Germany

Abstract
Global recognition of sustainability appeared in the early 1970s as the rapid growth of the human population and the environmental degradation associated with increased consumption of resources raised concerns. Since 1987 a definition of sustainability is given by the Brundtland Commission. For a decade, sustainability has become a main challenge for manufacture because this could imply more competitiveness for manufacturer and because countries may use this issue as a trade barrier. While sustainability becomes an indispensable element, there are currently no scientifically convincing and widely accepted indicators for assessing sustainability. This paper presents the scope and boundaries of sustainability assessment and the aspects to be considered for selecting a proper set of indicators related to pressures, such as e.g. Methane emissions, and impacts, such as e.g. Climate change. Furthermore this paper also present a draft set of indicators within a novel approach for areas of protection.

Keywords:
Method, Evaluation, Indicator, Sustainability

1 INTRODUCTION

Global recognition of sustainability appeared in the early 1970s as the rapid growth of the human population and the environmental degradation associated with increased consumption of resources raised concerns. [1] The definition of sustainable development given by the Brundtland Commission, formally known as the World Commission on Environment and Development (WCED), is a development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" [2]. Despite some proposed indicator sets for companies and countries [3, 4, 5], there are currently no scientifically convincing and widely accepted indicators for assessing sustainability [6, 7, 8] – especially for products and manufacturing processes. Several comparative evaluations of alternative indicators have been done over the past years. A range of very different evaluation approaches has been used for this purpose [9]. As the first step for scientific robustness of a sustainability assessment, this paper focuses on identifying suitable indicators, presenting a framework for this. The aspects or criteria for indicator evaluation are presented here as well as the interim results.

2 TOP DOWN AND BOTTOM UP APPROACH

Generally there are three approaches to develop indicators: top down, bottom up and combination of both. The top-down approach aims at a comprehensive consideration of all scientifically relevant aspects of sustainability. The bottom-up approach starts from the currently available data and tries to transform them into representative sustainability indicators. [10] A combined top-down and bottom-up approach is considered to develop a complete set of ecological, economic and social sustainability indicators (See Figure.1).

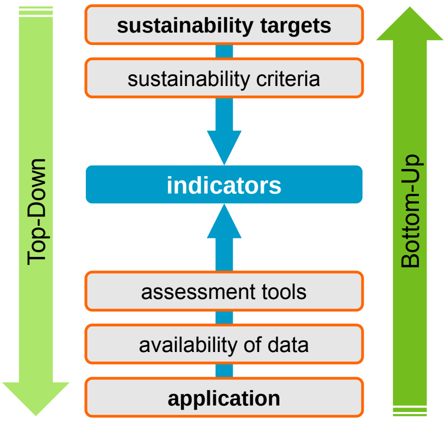


Figure 1: Sustainability indicators approach [11]

3 FRAMEWORK

3.1 Goal

First of all, it is an important step to identify what is the sustainability (goal of sustainability) before identifying proper set of indicators. There are many distinct approaches e.g. A = weak sustainability; B = weak sustainability operationalized; C = ecological economic strong sustainability; D = United Nations Environment Programme (UNEP) strong sustainability [12], (see Figure 2). For this research, the ultimate aim is taken in analogy from Meadows et al. 1972, which is "Materially sufficient, socially equitable, and ecologically sustainable" [1].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

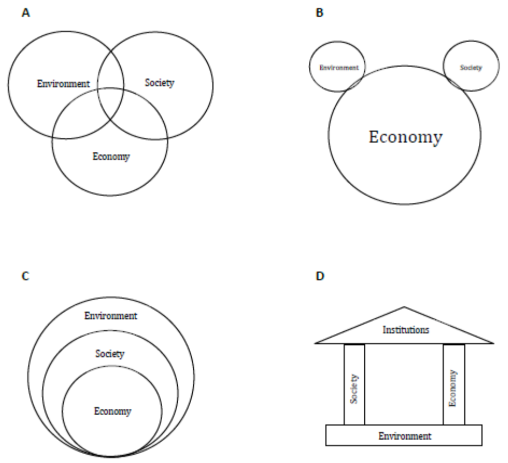


Figure 2: Sustainability approaches illustrated [12]

3.2 Scope - boundary and limitation

Next to identify the goal, next step is to define scope of the assessment, what is included and what not. The scope will help to judge also the relevance of the indicators. Here we refer to indicators is for manufacturing / production part of the society and related products. The focus is also the indicator that related to performance product, company or nation. Moreover to avoid subjective or individual preferable issues, the political, institutional and religion are not part of assessment.

3.3 Area of protection (AoP)

Instead of directly using the three pillars of sustainability Environment (Planet), Economy (Profit), and Society (People) , this approach groups the sustainability aspects in form of three different areas of protection, Ecosystem, Humans, and Resources, which connect the three pillars. (See Figure 3). The main reason to propose this AoP is often economic aspect is related or has a connection to social and environment pillars.

The three areas of protections are:

- **Resources**: This area of protection covers the indicators related to planet and profit. Moreover it indirectly covers resource-aspects related to people e.g. via profit for people.
- **Humans**: This area of protection covers the indicators related to people and profit.
- **Ecosystem**: This area of protection covers the indicators related to people and planet.

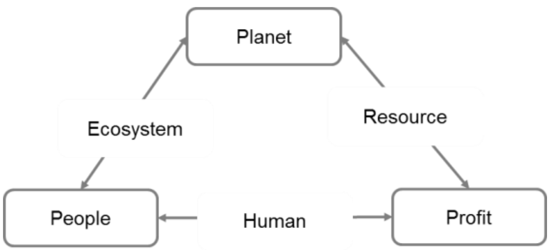


Figure 3: Illustration of relationship between the areas of protection and three pillars of sustainability assessment. (Own illustration)

4 INDICATOR EVALUATION

4.1 Methodology

For this paper only the top-down approach indicators are evaluated. The indicators are comprised from relevant initiatives, see 4.2. While these sets of indicators are applicable to all manufacturing, the level of relevance is different. For this evaluation, the experts have however to consider the global applicability, not in the specific one. In parallel, an semi-quantitative evaluation scheme is established. All criteria are considered equally important for these indicators, i.e. with an equal weighting. The overview of the methodology present in figure 4.

At this stage, a limited number of experts have carried out the evaluation, mainly to test the approach, to ensure that the wider survey later this year will have a solid foundation. The experts, anonymous, have received three sets of information: indicators for resources (8 resource topics, 15 indicators), humans (6 humans-related topics, 8 indicators) and ecosystem (14 ecosystem topics, 25 indicators), separately. In addition to provide the evaluation results for the indicators, for each area of protection, the experts rank the topics in order of priority.

Three levels are used for this evaluation: fulfills, partly fulfills and does not fulfill. These levels are represented by characters A, B, or C. The aim is not to make an absolute evaluation but to sort the indicators and identify the most suitable one(s). For each evaluation criterion, the research team has used the "mode" of the results to select the representative evaluation result for each criterion; table 1 illustrates this step. Like the statistical mean and median, the mode is a way of expressing, in a single number, important information about a random variable or a population. As next step, the research team has compared these evaluation results across the indicators addressing the same topic. The mode, the element that occurs most often in the experts' feedbacks of this sample is given in table 2.

For this preliminary result, the indicators have been evaluated by a small group of experts in the related areas i.e. Chemical Engineering, Environmental engineering, Industry ecology, Geoecology. This evaluation is based on expert judgment.

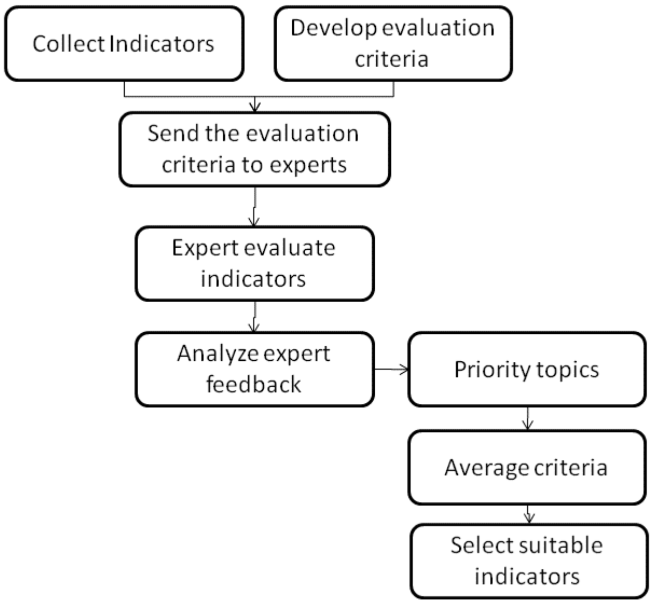


Figure 4: Overview of research steps

4.2 Source of indicators

The research team has compiled several indicators from well-known initiatives such as:

- European Commission Euro stat [13]
- EU Sustainable Development Strategy[14]
- Ecological Footprint network[15]
- Global Reporting initiative[16]
- European Commission Directorate General Environment[17]
- Circle of sustainability[18]
- Indira Gandhi Institute of Development Research[19]
- Ministry of Environment, Australia [20]
- Corporate sustainability management system [21]
- German National Sustainability Strategy[22]
- …

4.3 Evaluation criteria and aspects for indicator selection

Taking into account the desired characteristics of the framework for SDIs from the OECD proposed by Hart, the criteria to evaluate sustainability community are [22]:

- **Relevant** – an indicator must fit the purpose you have it for – help measure progress toward a goal, raise awareness about a critical issue, or help local decision-making regarding natural resource use, etc.
- **Understandable** – an indicator must be simple and easy for everyone to understand.
- **Reliable** – people must trust the information that an indicator provides.
- **Provides timely information** – an indicator must give information while there is time to act or correct the problem.
- **Looks at the entire system** rather than at isolated part of it – indicator should try to highlight the links among ecological, economic and social aspects.
- **Clear and easy to measure** – having (standard) procedure to measure and with limited effort.

The above criteria do not consider some technical and scientific aspects, why three more criteria are added:

- **Effectiveness -** must be pointing to right direction and relate to the technical and function performance.
- **Robustness -** must be scientifically sound/defendable, its calculation involve no or acceptable/limited subjectivity (i.e. be reproducible) and limited/acceptable uncertainty (i.e. be sufficiently precise).
- **Practicality** - must be applicable with acceptable cost and duration/ time consumption and still meeting sufficiently well the methods potential: The following needs to be given: sufficient data availability (considering data quality, technological broadness and specificity, geographical coverage, age), limited complexity of implementation / needs for experts, sufficient availability of tool support, acceptable duration for development, and others.

Table 1: Illustration of individual criteria evaluate. Exp. = expert

Criteria	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Mode
Understandable (U)	U_1	U_2	U_3	U_4	U_5	U_m
Relevant (R)	R_1	R_2	R_3	R_4	R_5	R_m
Reliable (Re)	Re_1	Re_2	Re_3	Re_4	Re_5	Re_m
Provides timely information (T)	T_1	T_2	T_3	T_4	T_5	T_m
Entire system (E)	E_1	E_2	E_3	E_4	E_5	E_m
Clear and easy to measure (C)	C_1	C_2	C_3	C_m	C_m	C_m
Robustness (RO)	Ro_1	Ro_2	Ro_3	Ro_4	Ro_5	Ro_m
Practicality (P)	P_1	P_2	P_3	P_4	P_5	P_m

5 RESULTS AND DISCUSSION

5.1 1st top down indicator set

Based on the first evaluation, the top down indicators for the three areas of protection - as example for micro-level questions - are:

Ecosystem

- Climate change - Radiative forcing as global warming potential over 100 years (CO_{2eq})
- Land use - Soil Organic Matter
- EcoToxicity - Comparative Toxic Unit for ecosystems (CTUe)
- …

Resources

- Land use - Soil Organic Matter
- Water use - Volume of water consumption (m3)
- …

Humans

- Human Health - Disability Adjusted Life Years (DALY)
- Human - Quality of life (QoL)
- …

5.2 Discussion

Currently many indicators especially from national level assessment e.g. European Union [13] focus more on the inventory level than on the entire system. However, this type of indicators has also many advantages e.g. understandable, clear and often easy to measure. In contrast with the comprehensive impact indicators, this needs scientific models, why it is often not easy to understand by some stakeholders.

Furthermore, many initiatives, e.g. UK [22] have a combination of inventory level indicators (e.g. CO2 emission) and impact assessment level indicator (e.g. Global Warming Potential (GWP)). This may lead to confusion and also wrong interpretation because it looks at the different level of the problem or concerning issue.

The state of the art of indicators for the environmental pillar of sustainability is the most advanced one, compared with the other two pillars. For the area of protection “Humans”, many indicators relate e.g. to living conditions, income, etc. but the impact of these two issues has not been derived (e.g. to express them as disability-adjusted life years (DALY), a measure of overall disease burden, expressed as the number of years lost due to ill-health, disability or early death).

The interim results presented in this paper are based on only a few experts and not all main indicators have been evaluated. Further work is needed. Finally, and based on the interim results, there is some overlapping in the selected indicators that needs to be solved.

6 ACKNOWLEDGMENTS

This study is funded by the German Research Foundation DFG (SFB 1026/1 2012). Moreover, we would like to thank the experts who spent their valuable time to provide us their opinions.

Table 2: Example of evaluation scheme (extract from original list of ongoing work)

Topic	Indicator	Understandable	Relevant	Reliable	Provides timely information	Entire system	Clear and easy to measure	Robustness	Practicality
Ecosystem									
River water Quality	Chemical oxygen demand (COD)	A	A	A	A	C	A	A	A
	Biological oxygen demand (BOD)	A	B	A	A	C	A	A	B
Air pollution	kg emission	A	A	A	A	C	B	B	A
Waste	Volume of waste	A	A	A	A	C	A	B	B
Waste	Mass of waste (kg)	A	B	B	A	C	A	B	B
Eutrophication	Accumulated Exceedance (AE)	B	B	B	A	A	B	A	B
Acidification	Accumulated Exceedance (AE)	B	B	B	A	A	B	A	B
	Acidification Potential (kg $NO_{2\ eq}$)	A	B	A	A	A	B	B	A
Climate change	kg CO_2	A	A	A	A	C	A	B	A
	Global warming potential-radiative forcing* (kg $CO_{2\ eq}$)	A	A	B	A	A	A	A	A
Ozone depletion	Ozone layer depletion (ODP)	B	A	A	A	A	A	A	A
…									
Resources									
Land use	Soil organic matter	A	A	A	A	A	A	A	A
	Area	A	A	A	A	B	A	A	A
Bird index	Number of bird index	C	B	B	A	C	A	A	A
Water use	Volume of water consumption	A	A	A	A	B	A	A	A
Resource depletion-mineral, fossil & renewable	Scarcity	A	A	B	A	A	B	B	B
…									
Humans									
Health and safety	DALY	B	A	A	A	A	B	A	A
	QALY	B	A	B	A	A	B	B	B
Wages and benefits	$	A	A	A	A	C	A	A	A
…									

Note: A = Fulfills this criterion, B = partly fulfills the criterion, C = does not fulfill this criterion

*Global warming potential over 100 years

7 REFERENCES

[1.] Meadows, D.H., et al., 1972 The Limits to Growth, ed. C.o. Rome., New York, NY: Universe Books.

[2] UN 1987 Report of the World Commission on Environment and Development: Our Common Future

[3] CSD - Commission of Sustainable Development: Indicators of Sustainable Development - Guidelines and Methodologies, New York, 2001.

[4] CSD - Commission of Sustainable Development: http://www.un.org/esa/sustdev/natlinfo/indicators/isdms2001/table_4.htm, version 25th June 2004.

[5] GRI – Global Reporting Initiative: Sustainability Reporting Guidelines. Boston, 2002

[6] Finkbeiner, M., Schau, E., Lehmann, A., Traverso, M.: Towards Life Cycle Sustainability Assessment. In: Sustainability, Volume 2, Issue 10, pp. 3309-3322, http://www.mdpi.com/2071- 1050/2/10/3309/, last call 15th Dec. 2010.

[7] Finkbeiner, M. 2009 : Vom Umweltschutz zur Nachhaltigkeit. Die Nachhaltigkeitsnutzwertanalyse unterstützt die Verwirklichung eines zentralen Paradigmenwechsel in Politik und Wirtschaft. In: MüllMagazin, Volume 2, pp. 4-9, Rhombos Verlag, Berlin.

[8] SRU - Rat von Sachverständigen für Umweltfragen: Umweltgutachten. Stuttgart, 1998.

[9] Wolf M-A., Chomkhamsri K., 2012, Selecting the Environmental Indicator for Decoupling Indicators, proceeding in Ecobalance International conference, Japan.

[10] Faucheux S, Hue S, O'Connor M, 2003: A bottom up/ top down methodology for indicators of corporate social performance in the European Aluminum industry

[11] European Commission, Joint Research Centre 2012: Towards a Life-Cycle Based European Sustainability Framework

[12] Scheumann R, Wolf K., Finkbeiner M.. 2012 Presentation A2-Sustainability indicator SFB 1026

[13] EEA, Environmental indicators 1999: Typology and overview in Technical Report No 25/1999. European Environmental Agency

[14] European Commission 2006: Review of the EU Sustainable Development Strategy (EU SDS)

[15] Global Footprint Network, 2009. Ecological Footprint Standards 2009. Oakland: Global Footprint Network. Available at www.footprintstandards.org

[16] Global Reporting initiative 2011: Sustainability Reporting Guidelines

[17] European Commission, DG Environment 2013: Communication from commission to the European parliament and the council Building the Single Market for Green Products Facilitating better information on the environmental performance of products and organisations

[18] McCarthy S., James P, Bayliss C., 2010 eds, Sustainable Cities, Vol. 1, United Nations Global Compact, Cities Programme, New York and Melbourne, 134pp.

[19] Salk H., Nathan K., Reddy S, 2008: A conceptual framework for development of sustainable development indicators

[20] Department of Sustainability, Environment, Water, Population and Communities: Measuring Sustainability program - Sustainability indicators for Australia - http://www.environment.gov.au/sustainability/measuring/indicators/index.html

[21] A.Azapagic 2003: Systems approach to corporate sustainability A general Management Framework

[22] Maureen Hart,; Guide to Sustainable Community Indicators, Second Edition: 1999

[23] DEFRA 2004: Sustainable development indicators in your pocket 2004 A selection of the UK Government's indicators of sustainable development

.

17.2 System Dynamic Optimization in the Sustainability Assessment of a World-Model

A. Fügenschuh[1], I. Vierhaus[2]

[1] Helmut Schmidt University / University of the Federal Armed Forces Hamburg, Germany

[2] Department Optimization, Zuse Institute Berlin, Germany

Abstract:

The System Dynamics (SD) methodology is a framework for modeling and simulating the dynamic behavior of socioeconomic systems. Characteristic for the description of such systems is the occurrence of feedback loops together with stocks and flows. The equations that describe the system are usually nonlinear. Therefore seemingly simple systems can show a nonintuitive, nonpredictable behavior over time. Controlling a dynamical system means to define a desired final state in which the system should be, and to specify potential interventions from outside that should keep the system on the right track. The central question is how to compute a globally optimal control? We propose a branch-and-bound approach that is based on a bound propagation method, primal heuristics, and spatial branching. We apply our new SD-control method to a model that describes the evolution of a social-economic system over time. We examine the problem of steering this system on a sustainable consumption path.

Keywords: System Dynamics; Mixed-Integer Nonlinear Optimization

1 INTRODUCTION

In sustainability science, the object of examination and the manipulation are often complex, large and dynamical systems [1]. These systems can be found on the macroscopic socioeconomic scale [2] as well as on the microscopic level in individual manufacturing processes (see [3] and the references therein). The reaction of these systems to external interventions can be counter intuitive, so that even when a quantitative goal has been identified and resources have been dedicated to achieving this goal, its implementation is non-trivial [4].

For this reason, the study of complex dynamical systems is an essential part of sustainability research. A traditional and successful approach to modeling dynamical systems is the System Dynamics (SD) methodology. SD was the basis for the report “Limits to Growth” [5], which introduced one of the first concepts of sustainability. For an introduction to SD and its applications we refer to Sterman [6].

SD models describe the behavior of a system that consists of several interrelated stocks, flows and feedback loops. The relation between those is usually determined by ordinary differential equations, nonlinear functional relations, logical relations (such as if-then-else), or tabular data. Even if each of these relations is individually well understood, the interplay of several of these relations can show a surprising, unexpected behavior in a simulation over time.

A System Dynamics model together with control functions and a real-valued objective function is called a System Dynamics Optimization (SDO) problem in the sequel. The need for an integration of optimization methods into the SD framework has been recognized already in the past. In previous approaches, different methods are used, such as nonlinear local optimization (for example, gradient search methods) or heuristics (such as genetic algorithms), which are essentially based on an “optimization through repeated simulations” approach, see [7, 8]. All these approaches have in common that they at best only provide feasible or local optimal solutions. Moreover, as pointed out by Burns and Janamanchi [9], nonlinear optimization methods rely on the availability of derivative information from sufficiently smooth functions. This restriction is in conflict with certain SD modeling elements, such as if-then-else clauses. In principle, all these methods cannot give a proof of global optimality or any other quality certificate of the computed solutions. The ultimate goal of our research is to fill this gap by developing a computational method that is able to handle all kinds of SDO models and yields feasible solutions as well as a certificate of optimality.

In the following we describe our approach to solve mixed-integer dynamic optimization problems that originate from SDO models. As a foundation we use the linear and nonlinear programming based mixed-integer nonlinear solver SCIP [10]. This framework already handles the input of an instance, the set up of the model’s variables and constraints, and the overall branch-and-cut solution process. Initially, we tried to solve SDO model instances using SCIP as a black-box solver off the shelf. Although SCIP is a highly capable general-purpose solver, it became clear that the special constraint structure of the SDO is for the most part intractable for the solver. However, if this structure is known and exploited to a high degree, the solution process can be fundamentally improved. In this paper, we will address the two aspects of the branch-and-bound solution approach, with the highest potential of improvement.

2 THE MINI-WORLD MODEL

We demonstrate our proposed methods using the *Mini-world* model introduced in Bossel [11]. It is a simplification of the much more sophisticated World3 model of Meadows et al. [5]. World3 uses 18 stocks, 60 parameters, 52 tabular functions, and around 200 equations to model the system's relations. Bossel's Miniworld is an aggregated version, that comes with just 3 stocks: the world population, the production (industrial, commercial, agricultural), which equals the consumption of goods, and the environmental pollution. Consequently, the number of parameters, tables, and equation relations are much lower. Interestingly, the model shows a qualitatively similar behavior compared to the much more evolved World3 model.

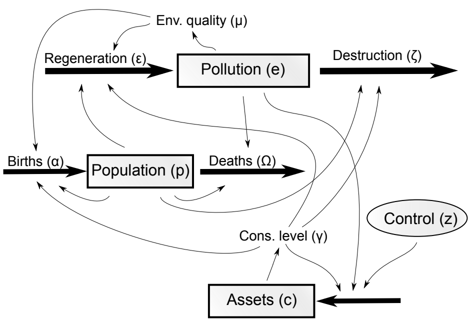


Figure 1: System Dynamics diagram for the mini-world control problem.

As discussed in Section 1, we will extend this model to an SDO, by introducing an objective function and a control mechanism. Our goal is to maximize the economic growth level, in order to provide a high standard of living to the world's population. However, if this standard would be too high, then a fast growing population would quickly consume its natural resources, and thus the population would collapse soon after. To prevent such behavior we introduce a population level ξ as a lower limit. The question we want to address is, how much sustainable growth can bear this mini-world at most for a population being at least ξ. The SDO diagram is shown in Figure 1. The corresponding mathematical model has four time-dependent functions: $p(t)$ for the population, $e(t)$ for the environmental pollution, $c(t)$ for the consumption, and $z(t)$ for the control function (the growth level).

2.1 MINLP Formulation

We apply an Euler forward discretization to the differential terms, with (Δt) being the size of a step in the time discretization. The continuous variables $p_i, e_i, c_i, z_i \in \mathbb{R}$ for $i = 0, 1, \ldots, T$ approximate the functions of the respective same name. Furthermore, we introduce the following real-valued continuous variables, each for $i = 0, 1, \ldots, T$: α_i are the number of births and Ω_i are the number of deaths at time step i. γ_i is the consumption level. μ_i describes the environmental quality. The environmental conditions change over time, and for this we introduce ε_i for the environmental recovery and ζ_i for the environmental destruction. The discretized SDO problem then reads as follows:

$$\max \sum_{i=0}^{T} z_i \tag{1a}$$

$$s.t. \; \frac{p_{i+1} - p_i}{\Delta t} = \alpha_i - \Omega_i, \;\; i = 0, 1, \ldots, T, \tag{1b}$$

$$\alpha_i = 0.03 \cdot p_i \cdot \mu_i \cdot \gamma_i, \;\; i = 0, 1, \ldots, T, \tag{1c}$$

$$\Omega_i = 0.01 \cdot p_i \cdot e_i, \;\; i = 0, 1, \ldots, T, \tag{1d}$$

$$\frac{e_{i+1} - e_i}{\Delta t} = \varepsilon_i - \zeta_i, \;\; i = 0, 1, \ldots, T, \tag{1e}$$

$$\zeta_i = 0.02 \cdot p_i \cdot \gamma_i, \;\; i = 0, 1, \ldots, T, \tag{1f}$$

$$e_i = e_i^+ - e_i^- + 1.0, \;\; i = 0, 1, \ldots, T, \tag{1g}$$

$$e_i^+ \leq 20.0 \cdot x_i, \;\; i = 0, 1, \ldots, T, \tag{1h}$$

$$e_i^- \leq 1.0 - x_i, \;\; i = 0, 1, \ldots, T, \tag{1i}$$

$$\varepsilon_i = 0.1 \cdot (1.0 - e_i^-), \;\; i = 0, 1, \ldots, T, \tag{1j}$$

$$1.0 = e_i \cdot \mu_i, \;\; i = 0, 1, \ldots, T, \tag{1k}$$

$$\frac{c_{i+1} - c_i}{\Delta t} = 0.05 \cdot \gamma_i \cdot e_i \cdot \left(1 - \left(\frac{\gamma_i \cdot e_i}{z_i}\right)\right), \quad i = 0, 1, \ldots, T, \tag{1l}$$

$$c_i = \gamma_i, \;\; i = 0, 1, \ldots, T, \tag{1m}$$

$$p_i \geq \xi, \;\; i = t, t+1, \ldots, T, \tag{1n}$$

$$p_0 = \bar{p}, \tag{1o}$$

$$e_0 = \bar{e}, \tag{1p}$$

$$c_0 = \bar{c}, \tag{1q}$$

$$p_i, e_i, e_i^+, e_i^-, c_i, z_i, \in \mathbb{R}_+, \;\; i = 0, 1, \ldots, T, \tag{1r}$$

$$\alpha_i, \Omega_i, \gamma_i, \mu_i, \theta_i, \varepsilon_i, \zeta_i \in \mathbb{R}_+, \;\; i = 0, 1, \ldots, T, \tag{1s}$$

$$x_i \in \{0, 1\}, \;\; i = 0, 1, \ldots, T. \tag{1t}$$

The change in the population p from time step i to $i+1$ is a result of the births α_i minus the deaths Ω_i in time step i (1b). The number of births α_i in time step i is proportional to size of the population p_i, the environmental quality μ_i, and the consumption level γ_i, where 0.03 is the proportionality factor (birth rate) (1c). The number of deaths Ω_i in time step i is proportional to the population p_i and the environmental pollution e_i, with a proportionality factor (death rate) of 0.01 (1d).

The change in the environmental pollution e from time step i to $i+1$ is a result of the negative environmental destruction ζ_i and the positive environmental recovery ε_i in time step i (1e). The environmental destruction ζ_i in time step i is proportional to the population size p_i and the consumption level γ_i (1f). Here 0.02 is the proportionality factor (environmental destruction rate). The environment is able to recover over time. If the environmental quality μ_i is above a certain threshold value (here 1.0), then the recovery ε_i in time step i is proportional to the environmental pollution e_i, with 0.1 being the proportionality factor (recovery rate). However, if the environmental quality μ_i is below the threshold value, then the recovery rate is no larger than 0.1 (1j). This is equivalent to a minimum function $0.1 \min(1, \mu_i)$, which is implemented with the auxiliary variables e_i^+, e_i^- and x_i and the additional constraints (1g), (1h) and (1i).

The change in the production and consumption c from time step i to $i+1$ is the result of a logistic growth function of Verhulst type (1l), which depends on both the consumption level γ_i and the environmental pollution e_i. The control variable z_i plays the role of the system's capacity (this is a constant in the original Verhulst equation). The constant value of 0.05 is a growth rate for the consumption. The consumption level γ_i equals the production c_i (1m).

The population p_i must not fall short of the given level ξ_i in each time step i (1n). Initially, in time step $i = 0$, the size of the population (1o), the environmental pollution (1p), and the consumption resp. production (1q) are given.

The system of equations and inequalities (1) completely defines the model. Setting $z_i = 0$ for all times i and choosing initial values p_0, e_0 and c_0 reproduces the Miniworld simulation or initial value problem (IVP).

2.2 Constraint Classification

We distinguish five types of constraints, that are typical for any SDO:

The discretized differential equations (1l), (1b), (1e) define the state variables p_i, e_i, c_i at a given time, in terms of the previous time.

The *explicit algebraic equations* (1c), (1d), (1f), (1j), (1k), (1k), (1m), define the algebraic variables on the left hand side. These equations depend on coinciding states and other coinciding algebraic variables.

The equations (1g), (1h) and (1i) define a *system of algebraic equations and inequalities* which implicitly but uniquely defines the algebraic variables e_i^+ and e_i^-.

Finally, equation (1n) defines a *linear state constraint*, and equations (1p),(1p) and (1q) defines *initial values* as mentioned above.

3 IMPROVING THE SOLUTION OF SDOS

In this section we will describe the proposed presolving bound propagation method and the proposed primal heuristic.

3.1 Primal Heuristics

Linear programming based branch-and-bound methods for solving mixed-integer linear and nonlinear problems are on the one hand today's method of choice for verifying the global optimality of a solution to a given instance of some model. On the other hand, they are also known for their actual weakness in creating such solutions. A pure branch-and-bound method can only come up with a feasible solution, if the linear programming relaxation of the current node is feasible for the non-relaxed model. This, however, is a rare exception. Thus it is necessary to provide feasible solutions from other sources. Having a good feasible solution early in the solution process allows to prune the search tree. Ideally, large portions of the otherwise exponential sized search tree do not have to be created and examined.

In modern MINLP solvers a large variety of different search strategies is used to construct feasible solutions, see [12–14] and the survey [15], for instance. These methods are designed and applied to general purpose MINLP problems. As reported by the respective authors, they are good in identifying solutions on a wide range of different problems. Some of them are readily available within SCIP. However, these have problems in finding solutions for dynamic MINLPs. This motivated our approach, which is presented in the following.

As described in Section 2, setting all controls in an SDO to zero, results in an IVP. If no path constraints like (1n) exist, then every solution of the IVP is a feasible solution of the SDO. From this, a fast primal heuristic for the model can be constructed. We set the control to a constant value for all times $z_i = z_c$ and then iterate the following steps for each discretized time i except $i = T$. We start at $i = 0$, where the states are given by the initial values:

1. Calculate the values of γ_i, μ_i, from the values of the state variable. Since every variable on the right hand side is fixed, we can treat the corresponding constraints as an equation with a unique solution.
2. Calculate the values of $\alpha_i, \Omega_i, \epsilon_i, \xi_i$, from the values of the states and the already calculated algebraic variables, by treating the corresponding constraints as equations as before.
3. Set $e_i^- = -\min(1, \mu_i), e_i^+ = \mu_i - e_i^-$ and x_i to 1 if $\mu_i > 1$, otherweise to 0.
4. Calculate the values of the state variables in $i+1$, using the values computed in steps 1, 2, 3.

This procedure can be easily generalized to general SDOs.

In one run of our current implementation, we attempt to construct two solutions fo the problem by setting $z_i = \bar{z}$ in the first, and $z_i = \underline{z}$ in the second run.

As mentioned above, this method may not yield a feasible solution if there are state constraints. To react to these cases, we add a check at the end of the propagation at each time if any state constraints are violated by the states calculated in the current step. If a violation is detected, we flip the control from $\bar{z}$ to $\underline{z}$ in the first run, and from $\underline{z}$ to $\bar{z}$ in the second run. It is also possible to backtrack a given number of timesteps, and apply the flip at an earlier point.

3.2 Presolving Bound Propagation

From the modelers perspective, it appears unnatural to give bounds to the states of the system. The definition of intial states or bounds on the initial states and bounds on the control already defines a finite state space, that should not be reduced by giving additional bounds. However, finding the exact bounds defining that state space is usually not possible in finite time. On the other hand, tight bounds are essential in speeding up the branch-and-bound process for two reasons. First, we apply linear programming to solve the subproblems in the branch-and-bound tree. If the variable bounds are weak, then the solution of the linear programs will also yield weak (upper) bounds for the solution of the MINLP. Second, when branching on a variable, it needs more branching decisions to fix a variable when the bounds are weak. Both issues are related to the solution speed and the memory requirement during the solution process. Hence in general, one is interested in obtaining good (narrow) bounds on all variables, assuming that the time spend for computing them is marginal compared to the gain in solving the overall problem.

A crucial step in solving mixed-integer linear or nonlinear problems is the preprocessing phase. In this initial step of the solution process, one tries to extract as much information as possible from the problem at hand. These information are implicitly contained in the model formulation, but hidden for the solver. The goal is to make them visible, so that the solver can use them to shorten the solution process. Preprocessing or presolving refers not just to a single method, but a whole bunch of various techniques, where some are more general, and others are more specific for certain problem structures. For more details and general surveys to MILP and MINLP solution techniques including preprocessing, we refer to [15–19].

In this section, we consider bound propagation in presolving. The usual approach for MINLPs is to consider each constraint individually, and to attempt the deduction of tighter bounds on each variable of the constraint from the bounds of the other variables [20]. For our model, this approach yields bounds that quickly diverge after the first few timesteps. This phenomenon of "exploding bounds" is characteristic for SDO problems, and could be avoided by consiering the full problem and solving the maximum and minimum problems for each state variables. However, the computational effort would be comparable to the original control problem, rendering this approach useless.

We propose a compromise between these two approaches. Instead of considering a single constraint, we formulate subproblems, by selecting constraints at a given time. We introduce the *lookback parameter* $h \geq 0$, which defines how far the problem extends in time. We define the subproblem at time i with lookback parameter h, as the subproblem $s_{t,h}$ consisting of the constraints (1b) through (1n), where $i \in \{t-h, t-h+1, \ldots, t\}$.

Our proposed bound propagation method iterates the following steps for each discretized time i except $i = T$, starting at $i = 0$:

1. Formulate the subproblem $s_{i,h}$.
2. For each algebraic variable v_i at time i:
   a) Solve the maximization problem $\max v_i$ subject to the constraints of $s_{i,h}$ to optimality and set the upper bound of the variable $\bar{v}_i$ to the solution value.
   b) Solve the minimization problem $\min v_i$ subject to the constraints of $s_{i,h}$ to optimality and set the lower bound of the variable $\bar{v}_i$ to the solution value.
3. For each differential variable w_{i+1} at time $i+1$:
   a) Solve the maximization problem $\max w_{i+1}$ subject to the constraints of $s_{i,h}$ to optimality and set the upper bound of the variable $\bar{w}_{i+1}$ to the solution value.
   b) Solve the minimization problem $\min w_{i+1}$ subject to the constraints of $s_{i,h}$ to optimality and set the lower bound of the variable $\bar{w}_{i+1}$ to the solution value.

The subproblems are solved with a time limit. If the time limit is reached before the problem is solved to optimality, the considered bound is set to the best dual bound.

4 COMPUTATIONAL RESULTS

For our computational experiments, we introduce a piecewise constant control with two states z_0 and z_1, where z_0 is valid for the first $T/2$ many time steps, an z_1 is valid for the second half of $T/2$ time steps. Then the objective function is a two-dimensional function depending on the values z_0, z_1 for the two constant controls. Figure 4 shows a contour plot of the objective function values for the two controls varying independently in the interval $[1, 10]$. Feasible solutions are in the lower-left corner. The black curve marks the borderline between the feasible and the infeasible region. Our goal is to keep the mini-world population above $\xi \geq 4$ (billion inhabitants). Any solution having less inhabitants is infeasible. Solutions in the infeasible region all fall short of the population lower limit of constraint (1n). A possibly optimal solution occurs for $z_0 = 1.79$ and $z_1 = 2.16$. This solution yields the highest total consumption level, while keeping the population size above the specified limit.

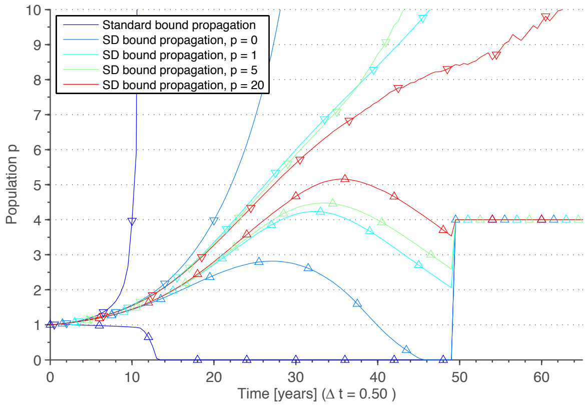


Figure 2: Presolved bounds for different look-back levels.

In Figure 3 we show three different solutions. The first for $z_0 = z_1 = 1$ is feasible but not optimal. The second for $z_0 = z_1 = 10$ is infeasible. (These two reference plots can also be found in Bossel [21].) Our potential optimal solution for $z_0 = 1.79$ and $z_1 = 2.16$ is shown as third plot.

Note that the plot in Figure 4 and the identification of an optimal solution is based on a number of simulation runs. Even if we use a fine grid, we cannot be absolutely sure that there is not a better solution that is hidden between two neighboring grid points. Our goal is to demonstrate that by using our bounding techniques we can cut off large portions of the search space. It is thus guaranteed that no better solution can be found in such cut off part.

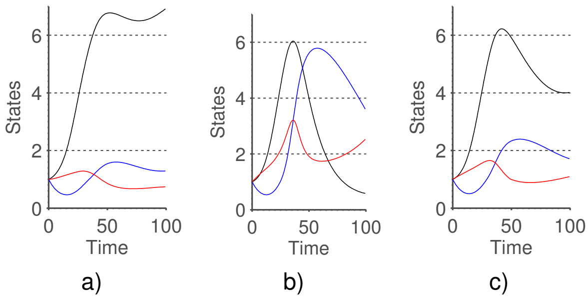


Figure 3: Black lines: p, blue: e, red: c. a): Feasible but suboptimal solution with control $z_0 = z_1 = 1$. b) Infeasible solution with control $z_0 = z_1 = 10$. c) Optimal solution with $z_0 = 1.79$ and $z_1 = 2.16$.

We apply our bounds strengthening presolve routine. The results for different look-back levels are shown in Figure 2 and Table 1. The SCIP-level (first line in Table 1) is special: The solver was very fast, but due to its numerical instability "proved" that the problem is infeasible (i.e., does not have a feasible solution), which is of course not true.

	presolve		branch-and-bound	
level	total time [h]	dual	dual	gap
SCIP	0.002	–	–	–
0	1.33	$6 \cdot 10^9$	625	$\gg 100\%$
1	4.42	640	638	71.1%
2	2.702	581	579	68.1%
5	4.53	508	506	63.5%
10	9.01	479	476	61.3%

Table 1: Computational results for different presolve look-back levels. Primal bound during branch-and-bound was 184.655 for all instances. Running time of the branch-and-bound runs was one hour.

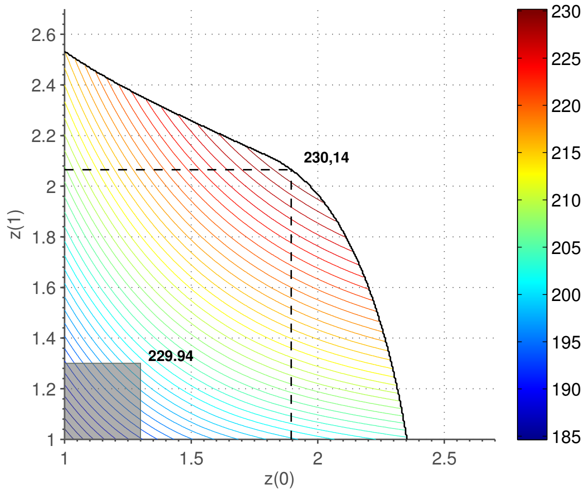


Figure 4: Objective function values for piecewise constant controls varying in $[1, 10] \times [1, 10]$. The (unique) optimal solution is in $(1.79, 2.16)$. The part of the control space with $z_1 \leq 1.3$ and $z_2 \leq 1.3$ marked by the gray box can be cut off. No better feasible solutions can be found in here.

A part of the search space that does not require further attention due to the bounding argument is shown in Figure 4. Here a look-back presolve level of 5 time steps was applied. Our optimal solution for $z_0 = 1.79$ and $z_1 = 2.16$ has an objective function value of 230.14. Any solution in the box defined by the green lines has an upper bound on the objective function value of less-or-equal 229.94, hence no better solution can be found in this part of the control space.

At the present stage of our implementation, we are, however, not able to prove that our potential optimal solution is indeed a global optimal one. The solver SCIP terminates, even in the highest presolve level, with a huge gap of 61.26%. Our ongoing research is devoted to close this gap to 0% within the given time limit, and to solve the problem for a control function with more than two constant segments.

5 SUMMARY AND CONCLUSIONS

We presented a System Dynamics Optimization (SDO) as an extension of classical System Dynamics Simulation (SD) model, by introducing a control mechanism and an objective function into the system. To solve such problems, we suggest mixed-integer nonlinear programming (MINLP) methods. We tested our methods on the mini-world SDO problem, and presented the results for several parameters.

We believe that our methods are generally applicable to all different kinds of SDO models. At the present stage of our work, each model needs to be individually analyzed and treated. We are working towards a black-box solver that a model will be able to use for his or her models in the same way SD simulation tools are used today. We think that having not only good-looking solutions, but additionally a certificate of optimality, is a further asset in practical applications.

ACKNOWLEDGEMENT

We gratefully acknowledge the funding of this work by the German Research Association (Deutsche Forschungsgemeinschaft, DFG), Collaborative Research Center CRC1026 (Sonderforschungsbereich SFB1026). The first coauthor conducted parts of this research under a Konrad-Zuse-Fellowship.

References

[1] Todorov, V., Marinova, D., 2011. Modelling sustainability. Math. Comput. Simul., 81(7):1397–1408.

[2] Scoones, I., 2007. Dynamic systems and the challenge of sustainability. STEPS working paper. STEPS Centre.

[3] Kibira, D., Jain, S., McLean, C. R., 2009. A System Dynamics Modeling Framework for Sustainable Manufacturing. In Proceedings of the 27th Annual System Dynamics Society Conference.

[4] Ghaffarzadegan, N., Lyneis, J., Richardson, G. P., 2011. How small system dynamics models can help the public policy process. Syst. Dyn. Rev., 27(1):22–44.

[5] Meadows, D., Meadows, D., Randers, J., Behrens III, W., 1972. The Limits to Growth. Universe Books, New York, NY.

[6] Sterman, J. D., 2000. Business Dynamics – Systems Thinking and Modeling for a Complex World. Irwing McGraw-Hill, Boston.

[7] Dangerfield, B., Roberts, C., 1996. An Overview of Strategy and Tactics in System Dynamics Optimization. Journal of the Operational Research Society, 47:405–423.

[8] Fu, M., 1994. Optimization via simulation: A review. Annals of Operations Research, 53(1):199–247.

[9] Burns, J. R., Janamanchi, B., 2007. Optimal Control and Optimization of System Dynamics Models: Some Experiences and Recommendations. In Proceedings of the 2007 Meeting of the Southwest Region Decision Sciences Institute.

[10] Achterberg, T., 2009. SCIP: Solving constraint integer programs. Mathematical Programming Computation, 1(1):1–41.

[11] Bossel, H., 2007. Systems and Models: Complexity, Dynamics, Evolution, Sustainability. Books on Demand GmbH, Norderstedt.

[12] Nannicini, G., Belotti, P., 2012. Rounding-based heuristics for nonconvex MINLPs. Mathematical Programming Computation, 4:1–31.

[13] Bonami, P., Cornuéjols, G., Lodi, A., Margot, F., 2009. A feasibility pump for mixed integer nonlinear programs. Mathematical Programming, 119:331–352.

[14] Berthold, T., Gleixner, A., 2013. Undercover: a primal MINLP heuristic exploring a largest sub-MIP. Mathematical Programming.

[15] Belotti, P., Kirches, C., Leyffer, S., Linderoth, J., Luedtke, J., Mahajan, A., 2012. Mixed-Integer Nonlinear Optimization. Technical Report ANL/MCS-P3060-1112, Argonne National Laboratory, Argonne, Illinois.

[16] Belotti, P., Lee, J., Liberti, L., Margot, F., Wächter, A., 2009. Branching and bounds tightening techniques for non-convex MINLP. Optimization Methods and Software, 24(4-5):597–634.

[17] Burer, S., Letchford, A. N., 2012. Non-convex mixed-integer nonlinear programming: A survey. Surveys in Operations Research and Management Science, 17(2):97–106.

[18] Fügenschuh, A., Martin, A., 2005. Computational Integer Programming and Cutting Planes. In R. W. K. Aardal, G. Nemhauser, editor, Handbook on Discrete Optimization, Series Handbooks in Operations Research and Management Science, volume 12. Elsevier, 69 – 122.

[19] Savelsbergh, M., 1994. Preprocessing and Probing Techniques for Mixed Integer Programming Problems. INFORMS Journal on Computing, 6:445–454.

[20] Berthold, T., Heinz, S., Vigerske, S., 2012. Extending a CIP Framework to Solve MIQCPs. In J. Lee, S. Leyffer, editors, Mixed Integer Nonlinear Programming, volume 154, part 6 of *The IMA Volumes in Mathematics and its Applications*. Springer Verlag, Berlin, 427–444.

[21] Bossel, H., 2007. System Zoo 3 Simulation Models: Economy, Society, Development. Books on Demand GmbH, Norderstedt.

17.3 Production Planning for Non-Cooperating Companies with Nonlinear Optimization

A. Fügenschuh[1], R. van Veldhuizen[2], I. Vierhaus[3]

[1] Helmut Schmidt University / University of the Federal Armed Forces Hamburg, Germany

[2] Social Science Research Center Berlin (WZB), Germany

[3] Zuse Institute Berlin, Department Optimization, Germany

Abstract:
We consider a production planning problem where two competing companies are selling their items on a common market. Moreover, the raw material used in the production is a limited non-renewable resource. The revenue per item sold depends on the total amount of items produced by both players. If they collaborate they could apply a production strategy that leads to the highest combined revenue. Usually the formation of such syndicates is prohibited by law; hence we assume that one company does not know how much the other company will produce. We formulate the problem for company A to find an optimal production plan without information on the strategy of company B as a nonlinear mathematical optimization problem. In its naive formulation the model is too large, making its solution practically impossible. After a reformulation we find a much smaller model, which we solve by spatial branch-and-cut methods and linear programming. We discuss the practical implications of our solutions.

Keywords:
Non-Cooperative Two-Person Games; Mixed-Integer Nonlinear Optimization

1 INTRODUCTION

Economists, politicians and entrepreneurs alike have been concerned with nonrenewable resources for a long time. Nonrenewable resources (e.g. oil, iron, zinc, phosphate, etc.) share the characteristic that they cannot be replenished within a relevant time frame. The economic literature on nonrenewable resources started with the work of Harold Hotelling [1]. Hotelling examined the case of a fully competitive market where extracting a marginal unit of the resource was costless. He showed that in this particular case, the price of the nonrenewable resource should increase at the rate of interest. More generally, it is the *shadow price* of the resource that should increase at the rate of interest. Both the specific and the more general result have become known in the literature as the *Hotelling rule*. Since Hotelling's seminal work, a large number of papers in economics have studied the Hotelling rule both mathematically and empirically under various assumptions (see e.g. Krautkraemer [2], Gaudet [3], or Kronenberg [4] for reviews of the literature).

A critical assumption in each of these studies is that producers of the nonrenewable resource act rationally in the economic sense. This entails that producers are -inter alia- assumed to maximize long run profits and are assumed to be able to do so in the optimal way. In the typical case when there are multiple active producers on the market, economic rationality means the outcome of the market can be characterized by a Nash equilibrium. In the context of nonrenewable resources, the Nash equilibrium entails that each producer has adopted the best possible (profit-maximizing) production strategy conditional on the *equilibrium* production strategy of all the other producers on the market.

However, in practice, many producers may not be following the Nash equilibrium production strategy. For example, the president of an oil producing nation may be more concerned about being re-elected than about maximizing long-term oil profits. In this case, he may not follow the Nash equilibrium production strategy but may instead produce at capacity in every period, to maximize short-term profits. A similar argument can be made for the CEO of a resource firm, whose bonus structure is unlikely to be based on long term profits. When some producers do not optimize, it will no longer be optimal to choose the Nash equilibrium production strategy even for producers who do optimize. Instead, they should maximize their profits given the range of possible production strategies they think the other producers on the market will adopt.

This article derives the profit maximizing strategy for producers who are faced with non-optimizing competitors. In particular, we will look at a market with two producers where one producer randomly chooses a production strategy from the set of possible production strategies. This approach is similar to the cognitive hierarchy (or level K) approach used in behavioral economics (see e.g., Camerer, Ho and Chong [5]). (Cognitive hierarchy theory assumes that different players have a different level of rationality, where level 1 best responds to level 0, level 2 best responds to level 1 (or a mix of level 0 and level 1), etc. The behavior of level zero players is typically assumed to be uniformly random; we will use a similar approach in this study.) We then solve for the optimal production strategy for the other producer on the market using spatial branch-out methods and linear programming.

The remainder of this article is structured as follows. In Section 2 we introduce the model that defines the players' payoff function, that rational players aim to maximize. We start in Section 3 with an analysis of the cooperative case, i.e., both players are able to communicate and thus are able to maximize their income. In general, forming such a monopoly would be not allowed, and hence we continue in Section 4 with the case that one player has to find a strategy to beat his competitor, irrespective of how the other player behaves. We discuss our results in Section 5. Conclusions are drawn in Section 6.

2 THE MODEL

We consider a two player game, where both players A and B make one simultaneous move for $n_t = 6$ consecutive rounds. Each player represents a producer, selling from its limited and nonrenewable product stock on a duopolistic market. In each round, each player has to decide on the number of products to sell. The price p that the players earn for one unit of their product depends on the total number of products offered by both players, and is computed according to the linear equation

$$p_t = \left(a - b(q_A^t + q_B^t)\right), \quad t \in \{1, 2, \ldots, n_t\}, \tag{1}$$

where a and b are parameters, q_A^t, q_B^t are the quantities sold by player A and player B respectively, and t is the current round. As abbreviation, we write q_i for the vector $(q_i^1, \ldots, q_i^{n_t})$ for $i \in \{A, B\}$. In each round, each player receives interest on the cumulative income of the previous rounds with an interest rate of $r > 0$. The values we use for our numerical studies are shown in Table 1.

After n_t rounds, the cumulative income from selling the product and from accumulating interest is added up, to yield the final payout $x_i(q_A, q_B)$ for player $i \in \{A, B\}$:

$$\begin{aligned} x_i(q_A, q_b) &= \sum_{t=1}^{n_t} \left(q_i^t \cdot p_t \cdot (1+r)^{n_t - t}\right) \\ &= \sum_{t=1}^{n_t} \left(q_i^t \cdot \left(a - b(q_A^t + q_B^t)\right) \cdot (1+r)^{n_t - t}\right). \end{aligned} \tag{2}$$

For a fixed value of q_B^t, the revenue of player A in round t, defined by $q_A^t \mapsto q_A^t \cdot p_t$, has a maximum at $\frac{1}{2b}(a - bq_B^t)$.

In Figure 1, the revenues $(q_A^t \cdot p_t)$ of player A for given values of q_A^t and q_B^t are represented in a contour plot (for t fixed). For a given value of q_B^t, there is one unique q_A^t with the highest possible revenue (shown by the red dashed line). Selling a larger number of products than this optimum will actually result in a *lower* revenue while selling *more* of the product in stock.

This property of the game leads to a high potential of conflicting strategies between the two players. It follows, that a good strategy must to be robust against unexpected decisions of the opponent.

The task of each player $i \in \{A, B\}$ is to choose quantities, such that his final payout x_i is maximized. The cases of continuous as well as integer quantities q_i^t can be considered. In practice, this will depend on whether the quantity is non-divisible (for example cars or cell phones) or divisible (for example raw materials).

The following criteria for a successful strategy can be derived from these equations:

- i Distributing the quantities evenly is preferable to selling everything at once, due to the decreasing price depending on the amount of product on the market.
- ii Having a high income in the earlier rounds is preferable to having a high income in the later rounds, due to the higher achieved interest.
- iii Since there is no information on the behavior of the opponent in the current round, the strategy should be as robust as possible against the decisions of the opponents.

Strategies (i) and (ii) are obviously contradictory, and also strategy (iii) can be in contradiction to strategies (i) and (ii), even though this is harder to quantify. Finding the best compromise between these criteria constitutes the desired solution that we aim to compute.

Letter	Parameter Name	Value
n_t	Number of rounds	6
r	Interest rate	.1
a	Maximum Price	372
b	Slope of price decay	1
s	Per player resource stock	170

Table 1: Overview of model parameters

3 COOPERATIVE CASE

To get a better understanding of the model, we first consider the cooperative case, where both players communicate in order to find the strategy that maximizes their combined income, and then strictly stick to this strategy over the time horizon. To find the highest possible combined income, we formulate the following nonlinear optimization problem:

$$\begin{aligned} \underset{q_A, q_B}{\text{maximize}} \quad & x_A(q_A, q_B) + x_B(q_a, q_B), \\ \text{subject to} \quad & \sum_{t=1}^{n_t} q_i^t \le s, \quad \forall i \in \{A, B\}. \end{aligned} \tag{3}$$

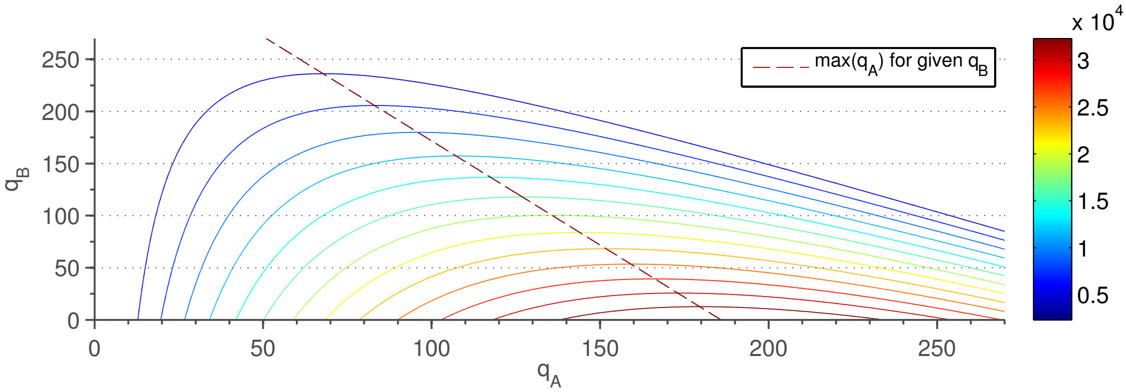


Figure 1: Contour plot of possible revenues of player A in a single round t for values of q_A^t and q_B^t. The broken, dark red line connects the highest possible revenues for given values of q_B^t, defined by $q_B^t = 372 - 2q_A^t$.

Since the final payout depends only on the sum of the quantities sold by the two players in each round, we introduce new variables q_c^t for the combined production and substitute $q_A^t + q_B^t = q_c^t$ (for $t = 1, 2, \ldots, n_t$) in the model formulation (3). This leads to a reduction of the size of the solution space, and thus a significant reduction of the solution time.

In a first experiment we set the per player resource limit to infinity, $s = \infty$. Then we receive the solution shown in Table 2 for q_c with a combined final payout of $2.669 \cdot 10^5$.

q_c^1	q_c^2	q_c^3	q_c^4	q_c^5	q_c^6
186	186	186	186	186	186

Table 2: Optimal solution for the cooperative case with $s = \infty$.

Since our reduced setup eliminates the motivations behind strategies (ii) and (iii), the optimal strategy is governed entirely by (i). We can argue that this is indeed the optimal solution, since it is the maximum of the income function in $q_A^t + q_B^t$ at each point in time $t = 1, \ldots, n_t$. Incidentally, this maximum is found at an integer quantity value, so the solution is optimal in the continuous as well as the integer case. In order to obtain a solution in the variables q_A^t and q_B^t from the values of q_c^t, we need to split the total production quantity among the two players A and B. In the integer case, there are $186^6 \approx 4.1 \cdot 10^{13}$ possible choices for q_A, q_B together that all sum up to the solution q_c and consequently have the same objective value. In the continuous case there are infinitely many distributions.

As a numerical solver for the nonlinear optimization problems we use SCIP. Information on the MINLP framework SCIP can be found in Achterberg [6], and in particular on nonlinear aspects of SCIP in Berthold, Heinz, and Vigerske [7]. Setting the per player resource stock to $s = 170$, we receive the continuous and integer solutions shown in Table 3.

	q_c^1	q_c^2	q_c^3	q_c^4	q_c^5	q_c^6
C	85.43	75.37	64.30	52.13	38.75	24.02
I	86	75	64	52	39	24

Table 3: Optimal solutions for the cooperative continuous (C) and integer (I) case.

We emphasize that the integer solution cannot be obtained by simply rounding the continuous solution to the nearest integer values ($q_c^1 = 85.43$ in the continuous case must be rounded up to $q_c^1 = 86$ in the integer case). The combined final income is $141,235$ in the continuous and $141,234$ in the integer case. This represents the optimal tradeoff between strategies (i) and (ii) for the given parameters.

4 OPTIMAL STRATEGY FOR AN UNKNOWN OPPONENT STRATEGY

In the next step, we will consider the non-cooperative game, where communication between the two players is not allowed. The usual approach for such a game is to find a Nash equilibrium. In a Nash equilibrium, the optimal strategy for player A would be the profit maximizing production strategy conditional on the *equilibrium* production strategy of producer B.

By contrast, our goal is to find an optimal strategy for player A, that is, a production schema that gives the highest possible yield from A, no matter what player B is doing. We will prioritize the robustness of the strategy for player A and therefore assume that player B does not necessarily follow a Nash equilibrium production strategy. In particular, we assume that player A has no information on the behavior of player B, and consequently, that every move of player B that respects the per player resource limit, occurs with the same probability.

The valid choice of quantities for one player in each of the six turns is called a trajectory. We define a set S

that consists of n_S trajectories of player B:

$$s_k = \left(q^1_{B,k}, q^2_{B,k}, ..., q^{n_t}_{B,k}\right), \quad k \in \{1, .., n_S\} \tag{4}$$

We assume that all trajectories in S are feasible in the sense that

$$\sum_{t=1}^{n_t} q^t_{B,k} \leq s. \tag{5}$$

Now we can define an new objective function as the average over the trajectories in s, assuming that each of the trajectories can occur with the same uniform probability of $1/n_S$:

$$\overline{x}_A = \frac{1}{n_S} \sum_{k\in S} x_A(q_A, q_{B,k}). \tag{6}$$

Then the new optimization problem reads as follows:

$$\begin{aligned} &\underset{q_A}{\text{maximize}} && \overline{x}_A, \\ &\text{subject to} && \sum_{t=1}^{n_t} q^t_A \leq s. \end{aligned} \tag{7}$$

The objective here is to maximize the mean income $\overline{x}_A$ of player A. Using the definition of $x_i(q_A, q_B)$, and changing the order of the two sums (the averaging over trajectories and the sum over the rounds), we can write

$$\begin{aligned} \overline{x}_A &= \frac{1}{n_S} \sum_{k\in S} \sum_{t=1}^{n_t} \left(q^t_A \cdot r^{n_t - t} \cdot \left(a - b\left(q^t_A + q^t_{B,k}\right)\right)\right) \\ &= \sum_{t=1}^{n_t} (q^t_A \cdot r^{n_t-t} \cdot (a - b(q^t_A + \underbrace{\frac{1}{n_S} \sum_{k\in S} q^t_{B,k}}_{q^t_{\text{eff}}}))). \end{aligned} \tag{8}$$

We have accumulated the averaging process in an *effective quantity* q_{eff} that expresses the average production. In order to solve (7) in the next step we need to specify the set of trajectories.

We create a set of trajectories S by discretizing the interval of possible quantities at a given time. The maximum quantity that can be produced is equal to the per player resource stock s. We select an integer value n_α. Then the production level for a certain time step can no longer be chosen arbitrarily, but must be an integer multiple of the basic step size $\delta := \frac{s}{n_\alpha - 1}$. That means, for each trajectory $k \in S$ and each time step $t = 1, \dots, n_t$ there exists such a multiplier $\alpha^t_{B,k} \in \{0, 1, 2, ..., n_\alpha - 1\}$, such that $q^t_{B,k} = \delta \alpha^t_{B,k}$. (Note that constraint (5) also needs to be fulfilled, still.)

The total production output of player B over all time periods $t = 1, \dots, n_t$ is also an integer multiplier of δ. For $\alpha \in \{0, \dots, n_\alpha - 1\}$ we denote by $S_\alpha \subseteq S$ those trajectories from S with $\sum_{t=1}^{n_t} q^t_{B,k} = \delta\alpha$.

The cardinality of S_α is denoted by $n_{S_\alpha} := |S_\alpha|$. The value of n_{S_α} can be computed using the binomial coefficient:

$$n_{S_\alpha} = \binom{\alpha + n_t - 1}{n_t - 1} \tag{9}$$

Using the following combinatorial identity:

$$\sum_{k=0}^{m} \binom{n+k}{n} = \binom{n+m+1}{n+1}, \tag{10}$$

we can calculate the number of all possible trajectories

$$\begin{aligned} n_S &= \sum_{\alpha=0}^{n_\alpha - 1} n_{S_\alpha} = \sum_{\alpha=0}^{n_\alpha - 1} \binom{\alpha + n_t - 1}{n_t - 1} \\ &= \binom{n_t + n_\alpha}{n_t} = \frac{(n_t + n_\alpha)!}{n_t! n_\alpha!}. \end{aligned} \tag{11}$$

Consider an arbitrary trajectory $k \in S$ with coefficient vector $(q^1_{B,k}, \dots, q^{n_t}_{B,k})$. Then any permutation of these coefficients leads to feasible trajectory, since the total production does not change by permuting their order. Hence summing the coefficients for any fixed time step t always yields the same constant value:

$$\sum_{k\in S} q^1_{B,k} = \sum_{k\in S} q^2_{B,k} = \ldots = \sum_{k\in S} q^{n_t}_{B,k}, \tag{12}$$

hence

$$\sum_{t=1}^{n_t} \sum_{k\in S} q^t_{B,k} = n_t \cdot \sum_{k\in S} q^1_{B,k} = \ldots = n_t \sum_{k\in S} q^{n_t}_{B,k} \tag{13}$$

follows. In particular $q^1_{\text{eff}} = \ldots = q^{n_t}_{\text{eff}}$, and we simply write q_{eff} in the sequel.

We can express the left-hand side in (13) as follows:

$$\sum_{t=1}^{n_t} \sum_{k\in S} q^t_{B,k} = \sum_{\alpha=0}^{n_\alpha - 1} n_{S_\alpha} \cdot \delta\alpha, \tag{14}$$

and, using the identity of (9), arrive at the following expression for q_{eff}:

$$\begin{aligned} q_{\text{eff}} &= \frac{\delta}{n_t n_S} \sum_{\alpha=0}^{n_\alpha - 1} \alpha \frac{(\alpha + n_t - 1)!}{(n_t - 1)! \alpha!} \\ &= \frac{\delta}{n_S} \sum_{\alpha=0}^{n_\alpha - 1} \frac{(\alpha + n_t - 1)!}{(n_t)!(\alpha - 1)!} \\ &\overset{(10)}{=} \frac{\delta}{n_s} \binom{n_t + n_\alpha}{n_t + 1} \\ &\overset{(11)}{=} \delta \frac{n_t! n_\alpha!}{(n_t + n_\alpha)!} \frac{(n_t + n_\alpha)!}{(n_t + 1)!(n_\alpha - 1)!} \\ &= \frac{\delta n_\alpha}{n_t + 1} = \frac{s}{n_t + 1}. \end{aligned} \tag{15}$$

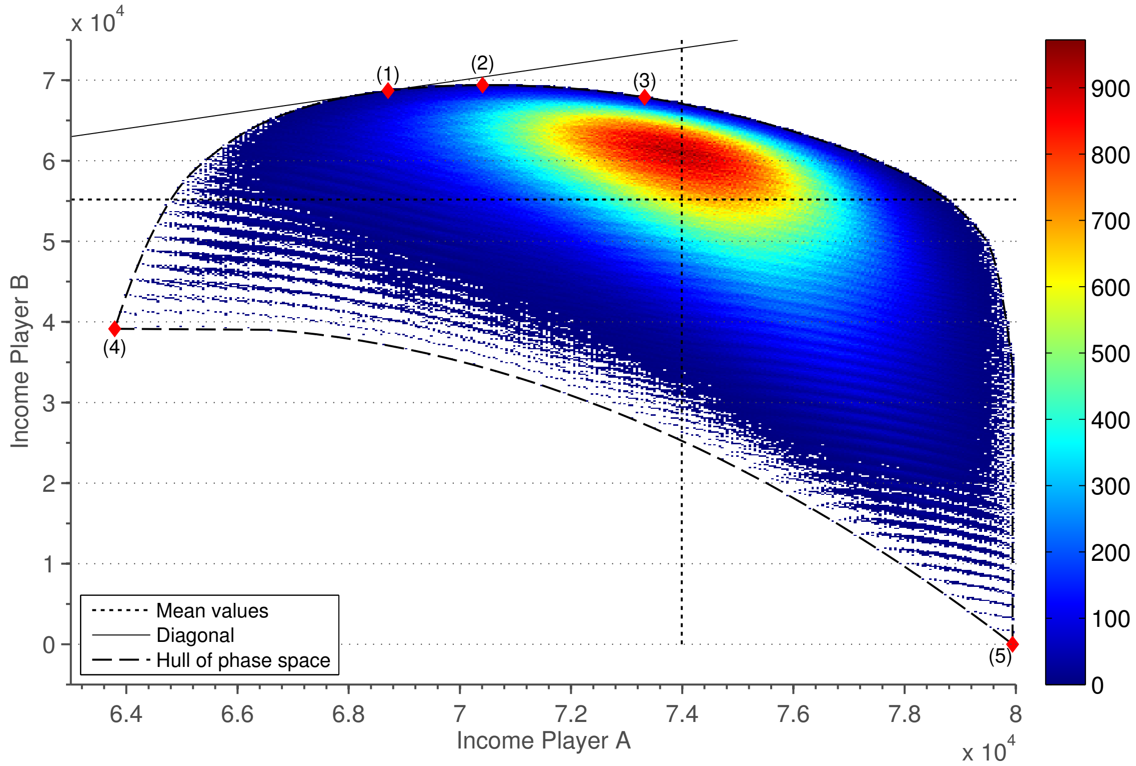


Figure 2: Plot of possible incomes for strategy 4 of player A and an equidstantly discretized set of trajectories for player B with stepsize $170/40$. Marked points are: (1): (68708,68708), symmetric strategy, (2): (70409, 69395) highest income of B, (3): (73325, 67898), highest combined income, (4): (63789, 39151), lowest income of A, (5): (79943, 0), lowest income of B, highest income of A, lowest combined income

We emphasize that we obtained an expression for q_{eff} that does not depend on δ, the step size of the discretization. Accordingly, the averaging over trajectories in the calculation of the total income of player A reduces to:

$$\overline{x}_A = \sum_{t=1}^{n_t} q_A^t \cdot r^{n_t - t} \cdot \left(a - b \left(q_A^t + \frac{s}{n_t + 1} \right) \right). \quad (16)$$

We have shown that the optimal solution of (7) is independent of the stepsize of the discretization. It is also straightforward to show that (16) holds for the case $\delta \to 0$, where in the limit the summation in (7) is replaced by integration.

Using (16), problem (7) is easily accessible with standard nonlinear global optimization techniques. The optimal solution for the continuous and integer cases, obtained by the solver SCIP, are summarized in Table 4.

	q_c^1	q_c^2	q_c^3	q_c^4	q_c^5	q_c^6
C	59.31	47.87	35.28	21.36	6.17	0.00
I	59.00	48.00	35.00	22.00	6.00	0.00

Table 4: Optimal strategy (production schema) for player A in the case of an unknown strategy for player B, in the integer (I) and continuous (C) case.

The mean incomes achieved by both players, when player A always uses the integer solution, are $(\overline{x}_A, \overline{x}_B) = (7.3990 \cdot 10^4, 5.5192 \cdot 10^4)$.

5 DISCUSSION

In the previous section, we derived a strategy for player A, that will lead to his highest average income, if the opponent makes random decisions. In this section, the properties of that solution will be discussed.

We will assume, that we have advised player A to strictly follow the strategy shown in Table 4. The averaging process implies that the game is repeated an infinite number of times, however this will not be the case in practice, therefore we will consider the possible scenarios that can occur in a single game under the given assumptions.

To allow for a visual interpretation, a diagram of the phase space of the game is shown in Figure 2. The diagram shows the incomes of players A and B, where player A uses the integer strategy in Table 4, and player B uses one of $10.7 \cdot 10^6$ trajectories that result from an again equidistant discretization of all possible trajectories with step-size $\delta = 170/40$. The number of points (i.e., trajectories) at a given pixel are represented by shades of color.

Some extreme points are marked in Figure 2. The lower right corner of the space is defined by the point where player B achieves zero income with the trajectory $q_B^1 = \ldots = q_B^6 = 0$. At the same time, this is the point where x_A is at its maximum, since player A achieves the highest possible prices. This is also the point, where the combined income of both players has the lowest value. The left corner of the phase space is marked by the minimum of x_A. The corresponding trajectory of player B is $q_B = (170, 0, 0, 0, 0, 0)$, which means that player B sells all his products in the first round. Due to the interest element of the model, this is the biggest possible disturbance of player A. However, this strategy is not beneficial for player B, as it yields a sub average income.

The highest combined income of $141,224$ is achieved when player B follows the trajectory $q_B = (25.5, 25.5, 29.75, 29.75, 34.00, 25.5)$. The achieved combined incomes are very close to the optimal solution in the cooperative case, however the income of player A is 8% higher than that of player B.

Player B achieves his highest possible income with the trajectory $q_B = (46.75, 38.25, 34.00, 25.50, 21.25, 4.25)$. This results in a sub average income for player A, however, player A still has a higher income than player B. In fact, we find that the every point of the phase space is below the diagonal. In other words, if player A follows the strategy in Table 4, there is no way for player B to achieve a higher income. Due to the symmetry of the model, it is of course possible for player B to achieve exactly the same income, by using the same strategy as player A.

From Figure 2, it is also clear that both players following the strategy in Table 4 cannot be a Nash equilibrium, since a different trajectory is optimal for player B. Van Veldhuizen and Sonnemans [8] derive the (feedback) Nash equilibrium for the same parameters using a backward induction type procedure. Our results show that the strategy in Table 4 means that player A will overproduce relative to the Nash equilibrium. Intuitively, player B will on average produce less than the Nash equilibrium in earlier periods and more in later periods, meaning it is optimal for player A to shift his production to earlier periods in response.

In a given instance of the game, there is still some room for improvement of our advice for player A, by using the information gained each round on the choices of player B. This leads to an iterative approach, where we first calculate the strategy in Table 4, and advise player A to choose the corresponding quantity in the first round. When player B has made his move, we can derive a new upper bound s, for player B, based on the amount of his product he has sold in the first round. Based on this, we can compute a *refined* strategy for the second round. We can iterate these steps each round, deriving a strategy that dynamically uses all the available information.

6 CONCLUSIONS

In this paper, we took a statistical approach to finding an optimal strategy for a two-player game that arises in the context of nonrenewable resources and the Hotelling rule. By stochastical considerations we reformulated a potentially large optimization problem to one that can be quickly solved to optimality using a standard branch-and-bound approach. Using the reformulated problem, we computed a strategy, that is unbeatable by the opponent in the sense that the opponent is not able to achieve a higher income, no matter what production strategy he might follow.

ACKNOWLEDGEMENT

We gratefully acknowledge the funding of this work by the German Research Association (Deutsche Forschungsgemeinschaft, DFG), Collaborative Research Center CRC1026 (Sonderforschungsbereich SFB1026). The first coauthor conducted parts of this research under a Konrad-Zuse-Fellowship.

References

[1] Hotelling, H., 1931. The Economics of Exhaustible Resources. Journal of Political Economy, 39:137–75.

[2] Krautkraemer, J. A., 1998. Nonrenewable Resource Scarcity. Journal of Economic Literature, 36(4):2065–107.

[3] Gaudet, G., 2007. Natural Resource Economics under the Rule of Hotelling. Canadian Journal of Economics, 40:1033–59.

[4] Kronenberg, T., 2008. Should We Worry About the Failure of the Hotelling Rule. Journal of Economic Surveys, 22(4):774–93.

[5] Camerer, C. F., Ho, T.-H., Chong, J.-K., 2004. A Cognitive Hierarchy Model of Games. The Quarterly Journal of Economics, 119(3):861–898.

[6] Achterberg, T., 2009. SCIP: Solving constraint integer programs. Mathematical Programming Computation, 1(1):1–41.

[7] Berthold, T., Heinz, S., Vigerske, S., 2012. Extending a CIP Framework to Solve MIQCPs. In J. Lee, S. Leyffer, editors, Mixed Integer Nonlinear Programming, volume 154, part 6 of *The IMA Volumes in Mathematics and its Applications*. Springer Verlag, Berlin, 427–444.

[8] Van Veldhuizen, R., Sonnemans, J., 2012. Nonrenewable Resources, Strategic Behavior and the Hotelling Rule. Working Paper:1–55.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

17.4 Value creation in open source hardware models

H. Send [1], S. Friesike [1], A. N. Zuch [1], J. G. Steingrímsson [2], G. Seliger [2]
[1] Alexander von Humboldt Institute for Internet and Society, Berlin, Germany
[2] Department of Machine Tools and Factory Management, Technische Universität Berlin, Germany

Abstract
Open Source Hardware is an emergent bundle of technologies, practices, business opportunities, and regulatory approaches for collaborative manufacturing. Open Source Hardware has raised high expectations in regards to its potential in value creation networks and in regards to sustainability. To allow a clear understanding of the phenomenon, the underlying concepts like open source, online platforms, and collaborative practices are outlined in this article. We describe the state of the art in Open Source Hardware, potentials, opportunities, and challenges. Open Source Hardware based value creation is depicted by showing complementary business models and organizations. The potential contributions of Open Source Hardware to sustainability are shown. The article concludes by stating directions for future research to better understand the prerequisites and conditions of value creation for collaborative manufacturing.
Keywords:
Innovation; Open Source Hardware; Sustainable Manufacturing; Value Creation

1 INTRODUCTION

From an economic perspective, property rights in the form of patents are often cited as a necessary precondition for innovative firm activity. This holds especially true when the costs of product development are high as in the case of the manufacturing industry or high technology. In a patent regime a firm can recoup upfront investments by later selling either the product or its property rights [1] [2]. However, we find evidence that both firms and individuals engage in innovative activities and freely reveal their intellectual property even if patenting is not an option [3].

1.1 Value Creation

In the realm of Open Source Hardware (OSHW) this behaviour is evident by the number and the variety of design activities people engage in. Currently enthusiastic laymen, professionals, scientists and students spend numerous hours creating designs that are open and thus freely available to anyone. OSHW activities come in many forms, e.g., drawings of components ready to be manufactured, descriptions on how to assemble complex systems, or manuals and descriptions on how to manufacture or process goods.

People working in OSHW use platforms as showroom of their creations. OSHW platforms become hubs for digital fabrication and a sort of digital support group for users starting manufacturing businesses on their own [4] [5]. The possibilities to lower production costs and local/on-demand production [5] [6] [7] [8] [9] [10] draw further attention to OSHW.

Ueda et al. [11] seek to integrate economic, psychological, environmental and other layers into one value creation model. They argue that the environmental value of artefacts often contradicts their economic value and that therefore another approach towards value should be selected. This preferred approach takes the form of a conjoined value creation, a concept where network externalities play an important role, by providing parts of the value creation.

1.2 Value Creation in Manufacturing

Creating any valuable tangible artefacts requires a value creation system. An example for such value creation systems are manufacturing processes. They convert resource materials into parts and components. The parts and components are assembled into subassemblies, assemblies and later into finished goods. Tools, equipment and methods are required for the conversion of resource materials,. Furthermore, a worker that has the skills to apply the tools and knows how to operate the equipment is needed. Finally this value creation process has to be housed, managed, and secured under specific conditions. Such denotation of a value creation can be expressed as a value creation module [12].

The value creation system's generic framework or the factors of each value creation module can be referred to as *product*, *process*, *equipment*, *organization* and *human* [12] [13]:

Product: Specifies 'what' will be provided, in what quantity and what quality. In general, products refer to both tangible and intangible goods (services) but in the present paper the main focus will be on tangible ones. An example of a product would be a bicycle.

Process: The operations required for the value creation or 'how' is the product made. A series of processes form a chain and a series of chains form a network. An example of a process would be a separation process such as turning.

Equipment: Answers the question 'whereby' the product is produced, hence names the tools in use. The equipment can be a single or a set of tools, machines and systems that have the purpose of fulfilling a specific process function. Housing and auxiliary systems are parts of the equipment.

Organization: Denotes 'where' and 'when' the value creation takes place. 'Where' specifies the geographical location. 'When' indicates the dominant production approach, i.e. demand driven, forecast driven or stockpile driven.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

Human: 'Who' is responsible for the value creation? Humans operate, manage and control systems of value creation.

In case of OSHW we argue that the process, equipment and organization layers of the value creation are subjects to fundamental changes and offer potentials for new manufacturing developments. We describe the distributed process and organization below. In the case of open source software (OSS) researchers like Lerner and Tirole [14] explain the initially surprising engagement of many individual contributors by immediate and delayed payoffs that range from the fun of programming to career incentives to peer recognition. Open regimes increased the possibility of peer recognition. Here individual contributions instantly become publicly available and therefore can be discussed. Firms on the other hand are incentivized to engage in open source projects because they can either offer complementary products or they can compete in markets in which they would not be able to achieve a favourable position without open sourcing [14]. It has been intriguing to many to observe that commercial firms found strategies to symbiotically incorporate and leverage features of OSS.

Researchers argue that the lessons learned from OSS can be applied to understand the development of OSHW [15] [2] [16] [17]. Yet, Mellis and Buechley [18] find the collaboration in OSHW to be on a smaller-scale with fewer participants than in a typical OSS project. The investments in physical prototypes are higher and components are more complicated to be shared.

2 BUSINESS MODELS

Moore describes an economic ecosystem as a group of "interacting organizations and individuals" that coevolve around an innovation [19]. According to Moore such an ecosystem is necessary for an innovation to thrive because a business relies on external resources such as capital and partners. Competition and cooperation are central in the relationships according to Moore. Von Hippel argues that actors of different size will generate complementary innovations [20] because of their differing resources and incentives in some markets. The OSHW market can be seen as an ecosystem that is currently evolving and supports innovation in hardware through the heterogeneity of its constituents.

Keinz and Prügl [21] argue that user communities are more effective at identifying additional market opportunities for innovations thereby increasing the wealth created from a new technology. Chesbrough [22] describes a similar phenomenon on the firm level. Even more, for OSHW firms it is almost inevitable to collaborate with competing firms [23]. Generally, firms that open their platforms to other hardware firms greatly increase their innovation rate [24]. According to Snow new products and services can be best designed when firms share their knowledge and engage in collaborative relationships.

Value creation is carried out by networking companies: to combine the material flow from reverse supply chains and manufacturing of new products seems to be a successful way for value creation networks [25] [14] and an overall surplus can be achieved by interacting within the network of actors.

Not all of the designs and parts used by the following actors are completely open. But the idea of openness and free revealing is common to many of the actors in the following types.

Because OSHW is a global phenomenon supporting tools [26] especially the Internet to connect with collaborators, exchange ideas and designs [18] play a central role.

2.1 Type: Tinkerer/Maker

At the centre of the development of OSHW are the individual contributors who – as in the case of OSS – devote much time and thought to freely available designs as for example in the case of the developers of the arduino circuit board. While von Hippel states in earlier works that collective models of innovation are a sign of market failure [1] he later proves that some stakeholders like consumers will engage in open innovation despite of a functioning market because of interests that are complementary to the incumbent industry for instance when a product is only valuable to a very small market [21] as probably in the case of many special designs in the OSHW market.

Moilanden and Vadén [27] report a survey of the 3D printing community where the resources that are needed to produce products are shared among the participants in a distributed network. In the survey people are included who use 3D printers and who develop 3D printers and related software. This type of commons-based hardware peer-production is still seen as niche by Moilanden and Vadén. According to them the lack of software usability and social co-operation (within the communities) but also low public awareness, costs of material and the printers themselves cause bottlenecks to 3D printing which make the community "great for hackers and not so much for consumers" [22]. They also show that the members of the 3D printing community are predominantly makers and not consumers but that the consumer-side is growing.

Although the barriers to entry into the OSHW market for this actor type are immensely lower that in into industrial hardware production they still remain considerable because of various factors such as costs for material and machinery, patents and necessary skills. It is very probable that their motivation to contribute intellectual property is composed of different aspects such as individual needs for a solution, signalling effects of their work, the enjoyment of working a challenging task, and other incentives that are also found in OSS programmers [14].

2.2 Type: Manufacturing Service Providers

We define manufacturing service providers as professional 3D printing or laser cutting services that are offered to individual users by service providers. Mota [28] finds this market to grow and argues that in some cases these might serve to simply provide tool owners with a new source of income by increased use of own machinery.

Architects and teams of engineers use 3D models for a long time to repeatedly test their designs regarding functionality, aesthetics or assembly or consumer research. Numerous and often small firms offer 3D printing of appropriate files on a basis of upload and shipping of the printed goods. The printing services enable firms and individuals to access industry grade quality of 3D prints that they could otherwise not afford.

Examples of this category are: *i.materalise.com* and *materialise.com*. Materialise.com is a services provider aimed at professional customers as for instance Samsonite.

i.materialise.com has recently been founded as a pure online service branch of materialise.com to cater to the growing number of individual customers that want to 3D print less costly objects than a firm usually does.

Shapeways is a combination of the service provider and the platform type described below: Users can either choose to print an own 3D design via shapeways or order physical copies of many of the stored designs on shapeways. Like shapeways i.materialise.com has started to offer a still small set of 3D designs.

2.3 Type: Platforms

Platforms are repositories of 3D printing or laser cutting design files that offer users to upload and download designs, comment upon and improve the designs of others. While a plethora of platforms offers open source software in different contexts thingiverse.com is the only pure platform for 3D designs to our knowledge with a high number of available designs and active users.

Thingiverse.com is a platform and design repository initiated by MakerBot Inc., where users mainly users who already own a MakerBot 3D printer themselves [28] [5] can upload mostly open and free digital designs for physical objects to the design database. Other than on platforms like shapeways one can not only download the designs but also alter them by remixing them using the mashup options provided by the platform [28]. At Thingiverse all the designs are free to download and modify [28]. This and the fact that Thingiverse lists information about where a design derives from and what has been derived from it attracts even more users and thus creates an own system of creation, design and innovation [29]. Thingiverse shows that especially the possibility to modify designs is as attractive as experimenting with 3D printing; to create improvements is more often than not clearly welcome [8]. Thingiverse demonstrates how 3D printing can become part of everybody’s daily life [5].

2.4 Type: Platform/Service Combination

A larger number of combinations between platforms and service providers exist. Here, users can upload design files and get the objects manufactured or users can download files and print/make them themselves; platforms stand also for marketplaces where a community meets. Examples are shapeways.com and ponoko.com [28] [5]. Users can download/upload and/or change the files or just order design kits which will be physically delivered as with *ponoko.com* or *thingiverse.com*. Although online fabrication services are quite young and only a few years old they have grown immensely in their number and also in the variety of services they offer [28].

2.5 Type: OSHW Pure Player

Currently the pure player is mostly a business model that sells a small set of physical goods as kit. Anderson, who created the website *diydrones.com*, claims that the pure player business model is up to the user: paying the company to produce its product or doing it oneself [30] [8]. Examples of this category are Arduino, *MakerBot, Ultimaker* or *DIY Drones*.

Arduino is a microcontroller and a piece of OSHW, free for anyone to use, modify, or sell [31]. Thus, these companies create value by being very disruptive to already existing forms of organization including markets because of the complexity of the relationships between peer production and markets [32]. The most interesting fact is that this business is based on registered brands as legal form for the products such as the Arduino: instead of the patent the usage of branding through creative commons licensing creates value and if the copy gets sold they only have to credit the original Arduino group and pay a small fee to the Arduino group [32] [31] [33]. However, the real profit is not made by the licenses or by selling the boards itself but by working as consultant: sell expertise, knowledge, custom service and products around it [33].

From his own experience Anderson [30] describes how companies like *dyidrones* build upon the output of tinkerers. There are differences in capabilities between industrial and personal usage of 3D printers: Mota predicts the establishment of a new class of creators and producers [28]. When code is freely available it can be used in training institutions like universities thereby making actors familiar with the code and reducing the learning cost [14] One might argue that partly this effect is replicated in the case of OSHW companies. In an early study on OSHW Raasch et al. [17] distinguish between community-driven and company-driven open design projects and find several instances for both types.

2.6 Type: Open classical firms

The OSHW model can be seen as a competing model for classical firms as in the case of the oftentimes competing OSS and proprietary software. In the case of OSS Lerner and Tirole [14] describe the economic incentives for large investments by major corporations as for instance the possibility to generate symbiotical revenues through services for open source software.

Müller-Seitz and Reger [18] show that OSS approaches can be partially transferred to an OSHW development, but major parts need refinement, such as research and development (R&D).

Snow et al. [23] analyse new community-based organizational forms for innovation and commercialization, using data as illustrative case from Blade.org which is a “a community website for firms dedicated to the continuous development and commercialization of blade servers, a computer technology with large but unforeseeable market potential” [23]. The main difference to an open source community (that is organized around contributions to a commons that is collectively and privately exploited) is the direct support of commercial relationships among members of community: *Blade.org* seems to have had as its purpose the commercialization of a particular technology [23]. To be successful firms have “to embed themselves and their networks on a valuable new organizational form – a designed community of firms sharing knowledge and engaging in collaborative relationships with community partners to develop and commercialize new products and services.” [23]

Boudreau [34] distinguishes between firms granting ‘access’ to platforms (Apple model) and ‘control’ over platforms (Unix model). Especially modular systems can be opened up to collaboration partly. Boudreau finds an inverted U-curve for the effect of giving access on innovation performance and a much smaller effect of giving up control over a platform. Generally, firms that open their platforms to other hardware firms greatly increase their innovation rate.

Example*: Ford Motor Company,* Ford has released both a hardware and a software toolkit to interface with the data-bus of its recent cars. The system provides read-only access to life vehicle data like GPS data, speed, lights and so forth. Ford strives to “unleash the power of the open source hacker community” in innovation [35] by actively inviting their participation. The hardware toolkit is complemented with a software platform available at *openxcplatform.com* on which programmers can download existing modules, exchange ideas and upload their own extensions much like on other open source platforms.

The rationale behind the project and Ford’s investments can be explained by West and Gallagher [36] who explain that firms following an open innovation strategy will try to increase demand for own products by giving away technology. Also the project can be seen from a lead user perspective because in this way Ford will understand consumer needs by engaging with users who communicate needs and possible solutions long before they become commonplace.

2.7 Type: Consumers

Some authors see the consumer evolving to the center of production by mass customization and (local) on-demand production [7] [8] [9] [10]. Moilanden and Vadén [27] see the consumption of 3D printed products rising. Against this, Rischau [5] argues that digital fabrication as chance for the creation of individual personalized goods is still not recognized within society or by the customer, only after that value to digital fabrication would be created which further would release a demand for it from the industry.

Thus, mass customization through open hardware digital fabrication still seems to be a challenge: Sissons and Thompson [9] argue that 3D printing and digital fabrication in the sense of open source needs a policy framework not only for legal issues like intellectual property but also in terms of infrastructure and material supply to unlock the full potential of 3D printing and also guarding a consumer confidence in 3D printing by developing effective standards.

2.8 Further Types: Researchers, Activists, Consultants

Other types of actors in the OHSW market are researchers, activists, and consultants. Moilanden and Vadén [27] show by their survey that 3D printing is highly relevant for research and educational purposes and that activists still play a major role, as yet almost one third of the community members have been also members of a hackspace, a fab lab, or a similar group and that most of the community members have been involved in at least one open source project.

3 SUSTAINABILITY AND POTENTIALS

OSHW practices are frequently discussed in the context of increases in sustainability [37] [11] [8] [10]. Sustainable development is defined as “meeting the needs of the present generations without compromising the ability of future generations to meet their own needs” [38]. The concept of sustainability is comprised of three dimensions: the economic, environmental and social dimension. Sustainability has been accepted as urgent requirement and one of the biggest challenges that mankind currently faces [12].

3.1 Environmental Perspective

Many authors associate OSHW practices with a positive environmental impact [37] [11] [8] [10].

Waste reduction: Campbell et al. [10] associate additive manufacturing with a reduction of waste material and higher efficiency in raw material expenditure as well as a reduced carbon footprint through production near the site of usage respectively omission of global shipping. Also according to Campbell et al. on-demand production can lessen waste that arises in other manufacturing techniques through unsold quantities. The ability to produce on-demand and the resulting decrease in fuel consumption, pollution and surplus waste is also discussed as advantages of remanufacturing and using open hardware by Mota [28] and Anderson [30].

3.2 Social Perspective

The environmental aspect of sustainability can be seen as an inter-generational issue that is not impairing the life of future generations by today’s doings [39]. Equally important is the intra-generational issue of social sustainability meaning the equal possibilities of all participants in markets and society [39]. Many authors argue that OSHW can have an impact here as well (Balka et al. 2009 [26] [8] [10] Moore 2011 [40].

Democratized production: In this context the aspect of democratizing production [28] [32] [8] Ilan 2011 [41] and innovation [42] through open source knowledge towards a participatory society [4] is a broadly discussed topic.

Sustainability’s potential in open hardware lies in open innovation: Innovation cannot be privatized and shelved [8]. Business partners in an open community have to use designs that are inherently more sustainable than proprietary designs [8].

Inclusion of developing countries: Kogut and Metiu [43] see potential in open source because it works in a distributed environment and is therefore suitable for developing countries to participate in frontier innovation. Likewise, Salem and Khatib [44] claim that open-source hardware can contribute to bridging the technological, educational and cultural gaps between developing and developed countries and is thus an approach to sustainability in a social, economic but also ecological sense.

3.3 Economic Perspective

The assumed ecological and social sustainability of the OSHW production model need to be complemented with economic viability for the model to become relevant in the long run and have the anticipated ecological and social impact.

A collaborative community of firms and partnerships [23] [17] [8] [45] but also the collaboration with the (product) community – who’s motivation is high to collectively make something plus the rewards they face through participation [30] – are other business models to be looked at.

Local production: To go back to local production is an attractive possibility that is re-animated as business strategy by the open hardware’s possibilities. Because ideally through OSHW local producers can access designs and achieve the quality of a worldwide community [8] local production becomes more attractive.

To successfully develop sustainable business in open hardware and additive manufacturing (3D printing) can be achieved by reducing or eliminating the supply chain for many products. Campbell et al. [10] see additive manufacturing as way to eliminate distance from the material world: the STL files of 3D printed goods can be sent instantly to the other side of the planet and get printed in 3D. Campbell et al. claim that also the resources that are needed to actually print a STL design file should appear locally if the supply chain shall be reduced and shipping material can become be obsolete.

Pearce et al. [37] discuss 3D printing OSHW in the context sustainable technology production. They conclude that open source 3d printing is still in a ‘hacker/development’ stage and not yet ready for deployment in developing countries but they show the feasibility of village-level production and acknowledge a ‘clearly enormous potential’ to OSHW in developing countries.

High levels of innovation: Boudreau [34] sees two viable pathways for open strategies – “vibrant markets with diverse ideas and active experimentation” in the case of systems were diverse actors have complete access to the system or heightened innovation in systems where the owner of a technology grants access to diverse actors as in the above case of Ford.

High levels of design quality: As in the case of OSS anybody interested in a development is allowed to examine and improve designs that are made available under an OSHW license. The collaborative model of innovation and design is associated with raised quality levels because in this fashion a more diverse group of thinkers can be accessed that is likely to combine helpful knowledge from different domains [46].

Reduction in upfront investments: Tao et al. [47] introduce cloud manufacturing (CMfg), being a computing- and service-oriented manufacturing model, as possible solution to the problem of how to enhance resource utilization and reduce resource and energy consumption. They do not directly relate to OSHW but their concept very well reflects many aspects of the phenomenon. Due to reduced upfront investments and lower costs of entry for SMEs (small and medium sized enterprises) CMfg can lead to reducing of infrastructure and administrative costs.

Reduction of development time: The reuse of software modules in OSS has been shown to reduce the resources needed for a development while gaining speed at the same time (Haefliger et al. 2008) [48]. The modularity of OSHW projects enables users to do the same [18] [49].

3.4 Challenges

The viability of the OSS model is proven and its success indicates possibilities for a promising future of OSHW. Yet, the development of physical goods comes with several challenges.

Upfront investments: Although the upfront investments are considerably lower for 3D printing a piece than in injection moulding, often physical tests are necessary to evaluate potential solutions thereby requiring costly equipment [18]. OSS on the other hand requires no further investments than a computer and time.

Development time: When OSHW projects rely on volunteers for development Abdelkafi et al. [16] report slow progress or even nonexistent development schedules. Abdelkafi et al. [16] find supply and manufacturing to be challenges that are frequently mentioned by OSHW practitioners.

Small scale production: Campbell et al. [10] see limitations in additive manufacturing because it is currently not suitable for mass production and quite slow in pace and speed.

Cooperation and aptitude: Moilanden and Vadén [27] show that lacks of software usability and less social cooperation within the OSHW communities exist and that low public awareness of OSHW are the bottlenecks of OSHW technologies. They also note that most of the developers of OSHW have not used a 3D printer: ‘developers’ (64.5 %) and ‘paid developers’ (12.7 %) have not used 3D printing [27]. To establish OSHW as easy to use and as tool box to local production future research has to be done.

Certification and liability: Mota [28] asks who will be liable for the safety of home modified and fabricated goods. An anecdote points towards the need for new certification rules like the CE mark of ‘European Conformity’. Also Kleemann and Voß [50] discuss the issue of “underpaid innovators” in the context of crowdsourcing.

4 SUMMARY AND FUTURE WORK

This paper compiled actors in the OSHW market and explained the potentials of a growing OSHW community. All actors contribute to the system as a whole and for their part rely on resources contributed by other actors. Since the development is rather recent only a small number of pure OSHW firms were making more than one million US$ in revenues in 2010. This small number makes the system fragile and indicates that a lot of enthusiasm is needed to enter the market as a OSHW pure player. On the other hand, firms like *Ford*, *Facebook,* and *Nokia* have introduced interfaces, opened up hardware designs, or made designs available for extension adding relevance to the development.

Central to Moore’s article on business ecosystems is a description of a business system’s development. According to Moore in the birth stage cooperation pays well. Our description of the OSHW actors is accordingly distinguished by broad cooperation. Moore’s ensuing stage of expansion is distinguished by the ecosystem’s offering finding a broad market and its companies beginning to fight for market shares. Here cooperation declines and larger corporations with their marketing and sales power threaten to destroy smaller former partners. Shapeways’ substantial funding and makerbots pull back from a complete openness policy [51] might be early signs of this stage. Moore advises businesses to fight alternative products in that stage but has written his article long before Lerner and Tirole or von Krogh and von Hippel proved sustained cooperation economically reasonable when firms contribute to a commons and find ways to generate profits from complementary services.

In their pivotal discussion of OSS Lerner and Tirole propose three strategies of firms to profit from OSS [14]. Each of these pathways is feasible for OSHW, too. Firstly, they propose to make complementary offerings such as services to the open source good as a passive strategy, which one might find in the above example of *i.materialise.com*. Secondly, a firm can achieve a degree of governance by extensive contribution within open projects to offer complementary goods as in the famous razor blade model. Thirdly, intermediaries can be used to align external open developments so that they later can be of more use within the firm. The example of *Ford’s* openxc.com fits this approach.

Future research should explore viable pathways for open pure player and classic firms to leverage the potential of OSHW in a way that OSS has brought value to the digital realm. OSHW is a young topic that has registered strong interests from several directions. Research on the topic is pivotal as the coming years will show whether this way of manufacturing is truly the “next industrial revolution” [30] it has often been labelled as.

5 REFERENCES

[1] von Hippel, E. and von Krogh, G., 2003. Open Source Software and the "Private-Collective" Innovation Model: Issues for Organization Science Organization Science, 14(2): 209-223.

[2] Nuvolari, A. and Rullani, F., 2007. Curious Exceptions? Open Source Software and ‘Open’ Technology, in: St Amant, K. and Still, B. (Eds), Handbook of Research on Open Source Software: Technological, Economic, and Social Perspectives, Information Science Reference, Hershey, New York, NY, pp. 227-39.

[3] Allen, R. C., 1983. Collective invention. Journal of Economic Behavior & Organization, 4(1), 1-24.

[4] Mellis, D.A., 2011. Case Studies in the Digital Fabrication of Open-Source Consumer Electronic Products, Master thesis, Massachusetts Institute of Technology. Retrieved online from: http://web.media.mit.edu/~mellis/mellis-thesis-screen.pdf

[5] Rischau, J. J., 2011. Custom Digital Fabrication in Industrial Design. Thesis to Achieve Master’s Degree, University of Illinois at Urbana-Champaign, Urbana, I. L. Retrieved online at: https://www.ideals.illinois.edu/bitstream/handle/2142/26045/Rischau_Johann.pdf?sequence=1

[6] Grosskopf, L., 2012. 3D Druck. Personal Manufacturing, Computer und Recht 2012: 618-624.

[7] Ratto, M., and Ree, R., 2010. The Materialization of Digital Information and the Digital Economy, Knowledge Synthesis Report, University of Toronto, Canada.

[8] Bauwens, M., Iacomella, F., and Mendoza, N., 2012. Report: A Synthetic Overview of the Collaborative Economy, Orange Labs and P2P Foundation. Retrieved online from: http://p2p.coop/files/reports/collaborative-economy-2012.pdf

[9] Sissons, A., and Thompson, S., 2012. Three Dimensional Policy. Why Britain Needs a Policy Framework for 3D Printing, The Work Foundation, Big Innovation Center, Lancaster University.

[10] Campbell, T., Williams, C., Ivanova, O. and Garrett, B., 2011. Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing.Strategic Foresight Initiative, Atlantic Council. Retrieved online from: https://info.aiaa.org/SC/ETC/MS%20SubCommittee/Alice%20Chow_3D%20Printing%20Change%20the%20World_April%202012.pdf

[11] K. Ueda, K., Takenaka, T., Váncza J., and Monostori, L., 2009. Value Creation and Decision-Making in Sustainable Society, CIRP Annals – Manufacturing Technology 58: 681–700.

[12] Seliger, G., 2007. Sustainability in Manufacturing, Berlin: Springer Verlag Berlin Heidelberg.

[13] Heyer, Steffen, Steingrímsson, J. G., and Seliger, G., 2013. Identification and Promotion of Effective and Efficient Product and Material Cycles via Crowdsourcing. In: Re-engineering Manufacturing for Sustainability. Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013 pp. 329-333.

[14] Lerner, J., and Tirole, J., 2002. Some Simple Economics of Open Source. The Journal of Industrial Economics, 50(2): 197-234.

[15] Abdelkafi, N., Blecker, T., and Raasch, C., 2009. From Open Source in the Digital to the Physical World: A Smooth Transfer? Management Decision, 47/10: 1610-1632.

[16] Raasch, C., Herstatt, C., and Balka, K., 2009. On the Open Design of Tangible Goods. R&D Management, 39(4): 382-393.

[17] Müller-Seitz, G., and Reger, G., 2010. Networking Beyond the Software Code? An Explorative Examination of the Development of an Open Source Car Project. Technovation, 30(11-12): 627-634.

[18] Mellis, D. and Buechley, L., 2012. Collaboration in Open-Source Hardware: Third-Party Variations on the Arduino Duemilanove, Proceedings of the ACM 2012 conference on Computer Supported Cooperative Work. ACM.

[19] Moore, J. F., 1993. Predators and Prey: A New Ecology of Competition, Harvard Business Review 71: 75-75.

[20] von Hippel, E., de Jong, J.P.J. and Flowers, S., 2012. Comparing business and household sector innovation in consumer products: Findings from a representative study in the United Kingdom. Management Science, 58 (9): 1669-1681.

[21] Keinz, P., & Prügl, R., 2010.. A User Community-Based Approach to Leveraging Technological Competences: An Exploratory Case Study of a Technology Start-Up from MIT. Creativity and Innovation Management, 19(3), 269-289.

[22] Chesbrough, H. W., 2003. The Era of Open Manufacturing, Sloan Management Review, 44 (3): 35-41.

[23] Snow, C. C., Fjeldstad, Ø. D., Lettl, C., and Miles, R. E., 2011, Organizing Continuous Product Development and Commercialization: The Collaborative Community of Firms Model, Journal of Product Innovation Management, 28(1), 3-16.

[24] Boudreau, K., 2010. Open platform strategies and innovation: Granting access vs. devolving control. Management Science, 56(10), 1849-1872.

[25] Heyer, S, Grismajer, M., and Seliger, G., 2010. Collaboration in Value Creation Networks to improve Material Cycles. In: 43rd CIRP International Conference on Manufacturing Systems, Vienna.

[26] Balka, K., Raasch, C., and Herstatt, C., 2009. Open Source Beyond Software: An Empirical Investigation of the Open Design Phenomenon, R&D Management Conference.

[27] Moilanen, J., and Vadén, T., 2012, Manufacturing in Motion: First Survey on 3D Printing Community. Retrieved online from http://surveys.peerproduction.net/2012/05/manufacturing-in-motion

[28] Mota, C., 2011. The rise of personal fabrication. Proceedings of the 8th ACM conference on Creativity and cognition - C&C '11, 279. doi:10.1145/2069618.2069665

[29] Weinberg, M., 2013, What's the Deal with Copyright and 3D Printing, Whitepaper, Institute for Emerging Innovation. Retrieved online at: http://www.publicknowledge.org/files/What's%20the%20Deal%20with%20Copyright_%20Final%20version2.pdf

[30] Anderson, C, 2012, Makers. The New Industrial Revolution. Crown Business, an imprint of the Crown Publishing Group, a division of Random House, Inc., New York.

[31] Thompson, C., 2008, Build It. Share It. Profit. Can Open Source Hardware Work? Wired magazine,16 (11). Retrieved online from:

[32] Powell, A. (2012). Democratizing Droduction Through Open Source Knowledge: From Open Software to Open Hardware. Media, Culture & Society, 34(6): 691-708.

[33] Menichinelli, M., 2013. Retrieved online from: http://www.openp2pdesign.org/

[34] Boudreau, K., 2010, Open Platform Strategies and Innovation: Granting Access vs. Devolving Control, Management Science, 56(10), 1849-1872.

[35] Ford Motor Company, 2013, Ford OpenXC Platform is Now Open for Vehicle Data, Customizable Hardware and Open-Source Research, Ford Motor Company, Newsroom. Retrieved online from: http://media.ford.com/article_display.cfm?article_id=37582

[36] West, J., and Gallagher, S., 2006. Patterns of open innovation in open source software - Open Innovation: Researching a New Paradigm 8.

[37] Pearce, J. M., Blair, C. M., Laciak, K.J., Andrews, E. and Nosrat, A., Zelenika-Zovko, I., 2010. 3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development, Journal of Sustainable Development 3(4): 17-29.

[38] Brundtland, G. H. and World Commission on Environment and Development, 1987. Our common future. Vol. 383. Oxford: Oxford University Press.

[39] Borghesi, S., Vercelli, A., and Vercelli, A., 2008. Global Sustainability: Social and Environmental Conditions, Basingstoke England: Palgrave Macmillan.

[40] Moore, P., 2011. Subjectivity in the Ecologies of Peer to Peer Production. The Fibreculture Journal, 17:82-95.

[41] Ilan, Z. B., 2011. From Economy of Commodities to Economy of Ideas : Hardware as Social Medium. In: Organizational Strategies for managingl Design. The Design Management Institute. Boston M.A., pp. 45-53.

[42] Malone, E., and Lipson, H., 2007. Fab@Home: The Personal Desktop Fabricator Kit. Rapid Prototyping Journal, 13(4): 245-255.

[43] Kogut, B. and Metiu, A., 2001. Open-Source Software Development and Distributed Innovation Oxford Review of Economic Policy 17(2): 248-264.

[44] Salem, M. A., and Khatib, J. I., 2004. An Introduction to Open-Source Hardware Development, EETimes. Retrieved online at: http://eetimes.com/electronics-news/4155052/An-introduction-to-open-source-hardware-development

[45] Redlich, T., 2010. Open Production Gestaltungsmodell für die Wertschöpfung in der Bottom-up-Ökonomie. Doctorial dissertation, der Helmut-Schmidt-Universität/Universtität der Bundeswehr Hamburg, Germany.

[46] Jeppesen, L. B., Lakhani, K. R. 2010. Marginality and problem-solving effectiveness in broadcast search. Organization Science, 21(5), 1016-1033.

[47] Tao, F., Zhang, L., Venkatesh, V. C., Luo, Y., and Cheng, Y., 2011. Cloud Manufacturing: A Computing and Service-Oriented Manufacting Model. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225 (10), 1969-1976.

[48] Haefliger, S., Von Krogh, G., & Spaeth, S., 2008. Code reuse in open source software. Management Science, 54(1), 180-193.

[49] Ragan, S. M., 2012. The Thingiverse "Heart Gears" Phenomenon - A Physible Family Tree. Retrieved online from http://www.smragan.com/2012/06/11/the-heart-gears-phenomenon-a-physible-family-tree

[50] Kleemann, F., Voß, G. G., (with Kerstin Rieder), Science, Technology & Innovation Studies, 4(1): 5-26.

[51] Brown, R. 2012. Pulling back from open source hardware, MakerBot angers some adherent CNET News. Retrieved May 6, 2013, from http://news.cnet.com/8301-32973_3-57520633-296/pulling-back-from-open-source-hardware-makerbot-angers-some-adherents

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

17.5 Life cycle sustainability assessment & sustainable product development: A case study on pedal electric cycles (Pedelec)

Sabrina Neugebauer[1], Ya-Ju Chang[1], Markus Maliszewski[2], Kai Lindow[2], Rainer Stark[2] and Matthias Finkbeiner[1]

[1]Department of Environmental Technology, Technische Universität Berlin, Germany

[2]Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany

Abstract

Sustainability is one of the important topics in nowadays societies since it was brought up in 1987 from the Brundtland Commission. The comprehensive sustainability assessment investigates products and value chains in the environmental, economic and social dimension. However, a large share of worldwide industries so far only focus on particular issues, e.g. energy efficiency or greenhouse gas emissions, and thereby ignoring the significance of integrity to achieve an overall sustainability in product development and value chains. This paper focuses on adopting a Life Cycle Sustainability Assessment, covering all three dimensions via Life Cycle Assessment, Life Cycle Costing and social Life Cycle Assessment within a case study for Pedelecs. Through this case study, significant hotspots and key parameters in the life cycle of Pedelecs are identified and discussed. The findings serve for the further development of existing methodologies to complete the Sustainable Product Development.

Keywords: Life Cycle Sustainability Assessment, Sustainable Product Development, Sustainability, Pedelec, Manufacturing

1 INTRODUCTION

Sustainability is one of the important topics in nowadays societies and encompasses not only the environmental dimension, but also the social and economic one, as it was defined by the Brundtland commission in 1987 [1]. Consequently, a methodology to measure sustainability is getting extremely important.

Sustainability is from utmost importance within the development and production of consumer goods for all areas of human life.

In connection with mobility the consumer good “bike” is generally considered as environmentally friendly in terms of commuting [2]. A new way of cycling came up with the so called Pedal Electric Cycles (Pedelecs) supporting the general cycling with an electric motor charged by battery, which has never been evaluated by means of sustainability.

As a consequence one of the targets is to develop a methodological approach to qualify engineers for the development of sustainable Pedelecs. Therefore the provision of applicable methods for Sustainable Product Development (SPD) is a necessary requirement for the early development stages of this product.

Thereby the adoption of a Life Cycle Sustainability Assessment (LCSA), covering all three sustainability dimensions within a case study for Pedelecs may help to find a reasonable direction. Through this case study, significant hotspots and key parameters in the life cycle of Pedelecs are identified and discussed. The findings serve for the further development of existing methodologies to complete the Sustainable Product Development.

2 ASSESSING SUSTAINABILITY

In general there are two ways to achieve a sustainable development: either by adopting retrospective or prospective methods within the product development process.

A typical retrospective method is the LCSA covering the environmental, economic and social dimension of sustainability throughout the whole life cycle of a product. It assesses the impacts in between or at the end of a product development process, but hardly in advance.

Whereas guidelines, mind sets, checklists and design methods for SPD as a typical prospective method define sustainable parameters to be considered during the early stages of product development. However appropriate and applicable criteria have to be defined with respect to the consequences during all stages of the life cycle.

3 METHODOLOGY & APPROACH

Two Pedelecs[1] were chosen for the following case study, as the product Pedelec is suitable for the approaches of sustainability assessment and Sustainable Product Development, as:

- Pedelecs are of rising interest during the last five years on European and Asian markets [3]
- Pedelecs are often cited as green mobility in urban regions in respect to electro mobility [3]
- Pedelec sharing systems are already established in many cities [3]
- Pedelecs are transferable to different markets from developing countries to developed countries
- Pedelec data for case studies are already available [4]

Within this case study both prospective and retrospective methods are considered targeting the discovery of a reasonable and appropriate approach for assessing sustainability in practice.

3.1 Sustainable Product Development

Sustainable Product Development covers the entire product development process from the initial start of the product planning to the pre-arrangement of manufacturing, where it

[1] A Pedelec is defined as a bicycle with an electric motor assistance that is regulated by [5].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

aims to support the engineers within each phase of the product development process.

Several methods have been proposed in the last decades to minimize the waste of resources and to give detailed information based on historical evolution [6].

The majority of methods for SPD is focusing on environmental friendly solutions and sometimes neglects economic targets and almost always neglects social consequences.

Moreover, research has shown, that most of the methods are very specific and therefore, often hardly transferable to other applications [7]. Usually methods are tested within single case studies and do not focus on transferability to other applications and cases.

The implementation of existing methods are seldom straightforward and had many barriers to overcome [8]. It has been recognized that one-aspect optimizations for single life cycle phases may lead to rebound effects and shifting of burdens instead of coming to a more sustainable solution. Thus nowadays many methods in Sustainable Product Development are based on life cycle thinking aiming to predict the entire product life cycle in order to avoid burden shifting [9]. This results in a challenge for the assessment of sustainability in the early stages of product development. The effectiveness of Sustainable Product Development is dependent on detailed life cycle information, which are mostly not available in the early stages, but which would be needed for sustainable decisions [10] [11].

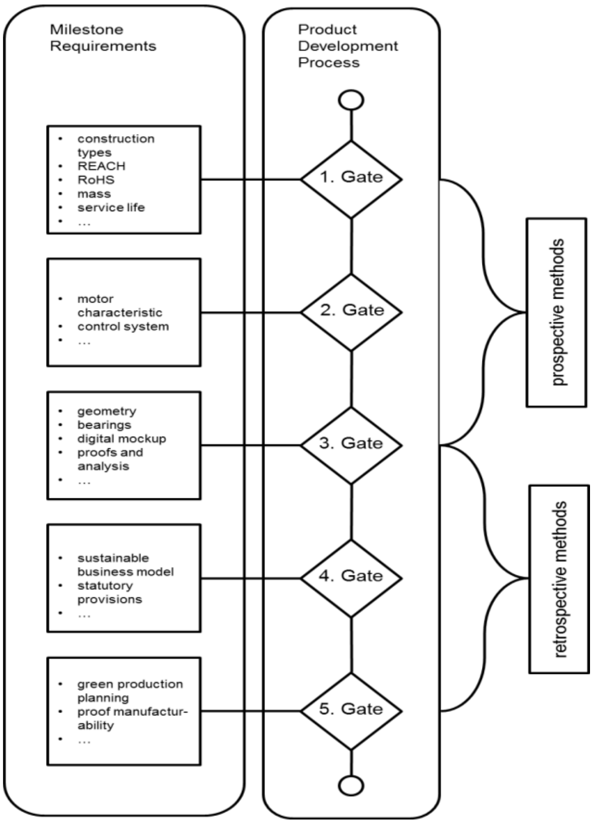


Figure 1: A generic product development process with milestone requirements and allocation of methods for SPD

In order to identify appropriate methods for each development step, a classification orientated on the product development process is proposed. Figure 1 shows a generic product development process with stages and gates. Exemplarily mile stones represent the different granularities in development; which are required to support methods for SPD.

Depending on user demands, intentions of application and several influencing factors from stakeholders, one method can be identified to support the SPD. By means of scientific questioning on every mile stone requirements of the product development process are defined as described in Table 1.

Table 1: Proposed categories and their attributes for classifying methods for SPD

CATEGORY	ATTRIBUTES
Orientation of the method	Prospective
	Retrospective
Type of method	Framework
	Design methodology
	Assessment
	Analytical method
	Checklist / Guideline
	Software
Who can apply the method?	Management
	Design engineer
	Sustainability assessment experts
	Process engineer
When in the product development process can the method be applied?	Product planning
	Conceptual Design/ Concept Development
	Embodied Design
	Detailed Design
	Prototype construction
	Production planning
Which dimension of sustainability is supported by the method?	Environmental
	Economic
	Social
Where on focuses the method in the product life cycle?	Raw material extraction
	Manufacturing
	Distribution
	Use
	End of Life
What is the abstraction level of the product that is supported by the method?	Requirements
	Components
	Product
	Process
	Service
What type of information is evaluated?	Quantitative
	Semi-quantitative
	Qualitative

The SPD is by now in the developing stage especially in connection with Pedelecs, as retrospective case studies are not available so far and scientific experience for suitable prospective indicators is lacking.

3.2 Life Cycle Sustainability Assessment

The LCSA method has been suggested for assessing sustainability by integrating Life Cycle Assessment (LCA) [12–14], Life Cycle Costing (LCC) [15], [16] and social Life Cycle Assessment (sLCA) [17]. LCSA can be formally expressed in the symbolic equation [18]:

$$LCSA = LCA + LCC + sLCA \quad (1)$$

The measurement of impacts concerning the environmental dimension of sustainability is the most advanced methodology within the LCSA framework. LCA is a standardized method [12] widely used to investigate the potential environmental impacts of products and services throughout the whole life cycle from cradle to grave [14]. The life cycle approach avoids shifting burden from one phase to another.

Environmental Life Cycle Costing (LCC) is proposed for the assessment of the economic dimension of sustainability, and builds further on the older Life Cycle Costing which has been used since the 1930s. However, it is relatively new within the sustainability assessment [15].

Social Life Cycle Assessment (sLCA) is a life cycle tool to assess the potential social and socio-economic impacts of products and their consumption throughout their life cycle. SLCA pays great attention to measure the impacts on workers, local communities, consumers and societies affected by the production and consumption of products [17], but is still in the development stage as a clear framework is so far missing.

The LCSA method is applied on Pedal Electric Cycles (Pedelec) covering all stages of the life cycle from production via use-phase to the end-of-life.

The LCA covers all relevant impacts by use of the ReCiPe method [19] on the mid-point and end-point level and the USEtox model [20]. ReCiPe covers 18 mid-point impact categories, like climate change, ozone depletion, freshwater eutrophication, human toxicity etc., those are referring to three end-point categories (damage to human health, damage to ecosystems and damage to resource availability). The USEtox consensus model displays human health and ecosystem characterization factors in connection with toxic substances.

Within the LCC in a first version consumer and labor costs are displayed representing the consumer and manufacturer perspective [15].

For the sLCA impacts in connection with working conditions, and labor rights are shown based on the Social Hotspot Database [21], [22], as the Pedelec is consisting of parts from several countries.

4 RESULTS OF THE PEDELEC CASE STUDY

Within the performed case study two Pedelec configurations (one Standard Pedelec and one Eco Pedelec) are assessed with different battery types, different frames and different seats. On the one hand the differences between the two types should be intimated, but in addition the main impacts for all three dimensions are to be displayed for Pedelecs in general.

4.1 Sustainable Product Development case study

Over 110 different methods for product development were identified and classified in a methodological data base that is constructed on the classifications previously described in Table 1. For this purpose, a product development process is in progress to define milestone targets for the method selection. Two methods, the guideline from [23] and D4S (Design for Sustainability) rules of thumb from [24], are selected to give support in identifying a more sustainable configuration for Pedelecs. The Standard Pedelec is derived from the European “Go Pedelec!” project [3] as a baseline configuration. The Eco Pedelec configuration was set up to proof the common opinion of environmental friendly products, which will be verified within the LCSA case study.

4.2 Life Cycle Sustainability Assessment Case Study

For the LCSA of the two Pedelecs all phases of the life cycle are included, beginning from the material production and the Pedelec manufacturing (including six different production-sites in six countries) over the use-phase (including also maintenance) to the end-of-life. The study is based on the functional unit of one Pedelec running for 15.000 km.

The manufacturing phase of the Pedelecs is divided into the single parts of the bike under consideration of the production-sites. The countries included are Germany, United Kingdom, Netherlands, Italy, Taiwan and Malaysia.

With regard to the use phase Germany is defined as the target market, where the Pedelec is used, which is important with respect to the electricity grid mix used for charging the battery.

Also the end-of-life is assumed to occur in Germany, wherefore German recycling processes are assumed.

Life Cycle Assessment

Even if the Eco Pedelec was assumed to generate less impacts especially on the environmental dimension the final result only shows a slight difference (exemplary results for Climate Change [kg CO2eq] see Figure 2). Although the Eco Pedelec performs a bit better during the use-phase due to less electricity consumption for charging the battery, no remarkable environmental benefits can be noticed throughout the life cycle of the Eco Pedelec.

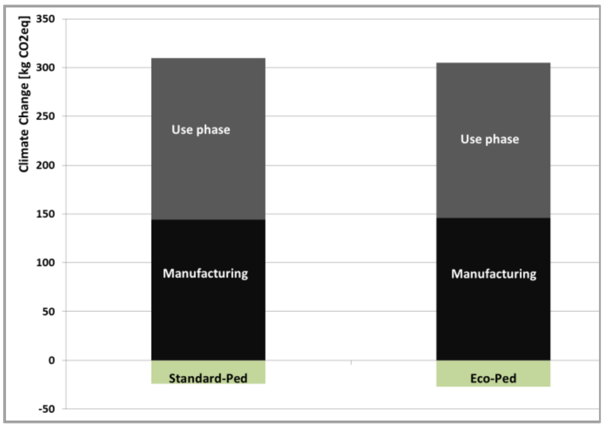


Figure 2 : Climate Change result for the Standard and the Eco Pedelec divided in Use-Phase, Manufacturing and EoL

The two main parts making a difference are the frame and the battery. Whereas for the Standard Pedelec a common aluminum frame is used, in case of the Eco Pedelec titanium is the frame material. The titanium frame weights with 1.4 kg a little less compared to the aluminum frame with 1.85 kg. However, the titanium frame performs worse in case of CO2eq (see Figure 3). This is caused by the higher environmental burdens of the raw material production for titanium compared to aluminum in case of Climate Change.

The same result can be recognized for the Primary Energy Demand (Eco Ped 369 MJ vs. Standard Ped 345 MJ) and the Ecotoxicity (Eco Ped 2.0 CTUeco vs. Standard Ped 0.5 CTUeco). Contrary are only shown for the Metal Depletion Potential where the titanium frame shows similar results compared to the aluminum one.

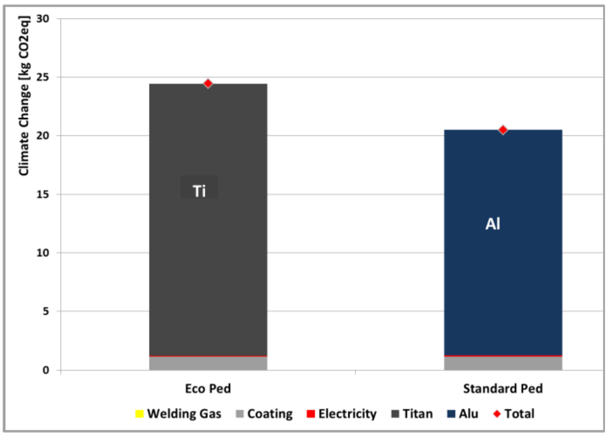


Figure 3 : Climate Change result for the Standard and the Eco Pedelec frame divided in material production and welding process

For the battery the Eco Pedelec performs better as a smaller battery with a greater range is used. Two beneficial effects can be determined here (see Figure 4): First the battery creates less production burden and second less electricity is needed during the use-phase for charging the battery. Similar results are detected for the Primary Energy Demand and the Ecotoxicity potential.

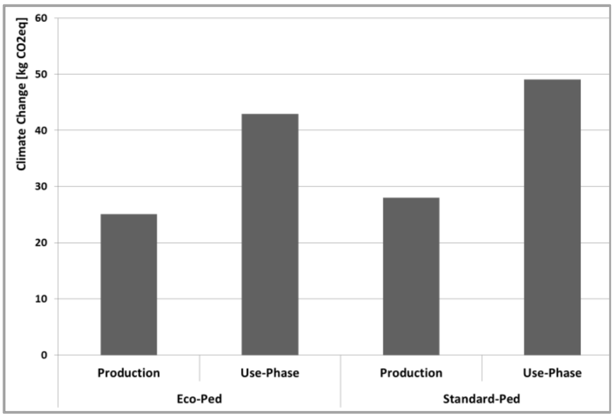


Figure 4 : Climate Change result for the Standard and the Eco Pedelec battery divided in material production and consumption during use-phase

Life Cycle Costing

Within the LCC in a first step the costs for the consumer over the life cycle of the two Pedelecs are studied and in addition the labor cost per part and country are analyzed.

The consumer costs consist of the purchase prices for the single parts, of the maintenance costs for replacing the tires during the life cycle and of the cost for charging the battery expressed in costs per kWh.

The resulting total consumer costs for the Eco Pedelec are 2,948 €, whereby the purchase of components has the biggest share with total 1,977 € (see a detailed view in Figure 5).

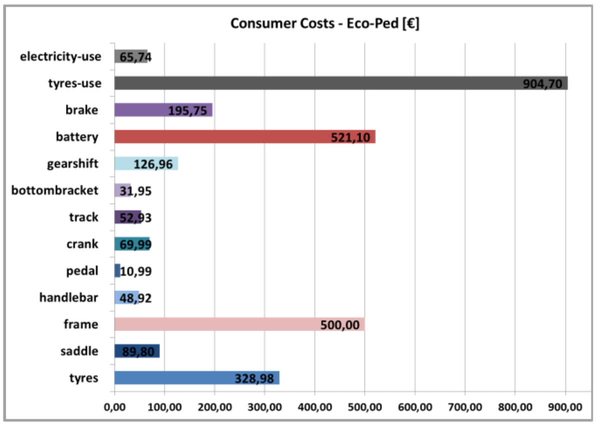


Figure 5 : Detailed consumer costs for Eco Pedelec parts and use-phase consumption

For the Standard Pedelec the total consumer cost is with 2,575 € a bit lower, as the purchase price for the Pedelec is 1,595 € (see detailed view in Figure 6).

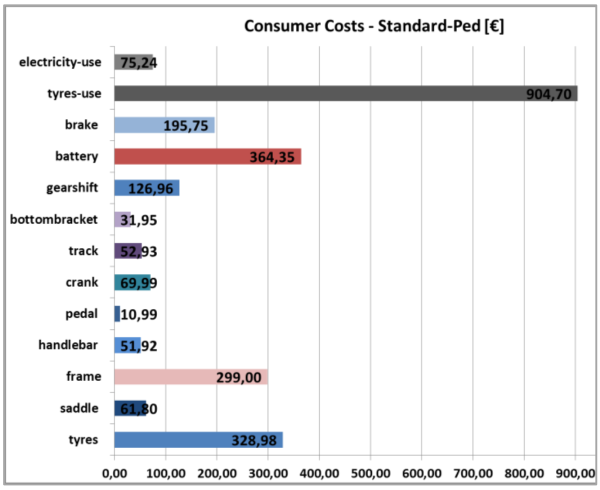


Figure 6 : Detailed consumer costs for Standard Pedelec parts and use-phase consumption

With regard to the labor costs every part was allocated due to the production-site in the related country. Six countries were identified to be relevant for the study: Germany, Netherland, United Kingdom, Italy, Taiwan and Malaysia.

In comparison the Standard Pedelec has less labor costs (total 150 €/Pedelec) than the Eco Pedelec (117€/Pedelec)[2]. The difference is caused by the production-sites of the frame production. The titanium frame for the Eco Pedelec is assumed to be produced in Germany; on the contrary the aluminum frame for the Standard Pedelec is coming from Taiwan, where most of the aluminum frames for all kind of bikes are produced. As the employee wage per hour in Taiwan is lower compared to the German one, the production of one aluminum frame is cheaper compared to the titanium frame. The lowest wage levels were found for Taiwan, Malaysia and Italy, but only for Taiwan a risk of not reaching the non-poverty wage line has been recognized. This will be further discussed in the sLCA part.

Social Life Cycle Assessment

The study of the social impacts related to the production of the two considered Pedelecs focused on the workers as a important stakeholder group. Beside that the labor conditions in the regarded countries are reflected.

The environment for the worker is strongly dependent on the place of work, which is connected to the country and also to the field of work. A clear distinction between the two types of Pedelecs cannot be given, as both Pedelecs consisting of parts from all six countries considered.

For the Pedelec production significant differences could be recognized in the wage level but also for the labor rights.

The highest risk of not reaching the non-poverty wage level was recognized for the parts (aluminum frame and saddle pillar) produced in Taiwan, as the average wage with 5.07 €/hour on the country level is already below to the non-poverty line of 5.55 €/hour [25], [26]. This might not be relevant for all employees in the value chain of the Pedelec production, but it is highly relevant for employees on the lower end of the production line, e.g. technicians.

Based on the Social Hotspot database the labor rights per country are observed, including child labor, forced labor, migrant workers, freedom of associations, labor laws, poverty, unemployment, wage assessment, and working time. The highest risk was identified for all parts (track and gear shift) produced in Malaysia (see Figure 7). The main drivers are the risk for child labor, the risk for forced labor, and the risk that the ILO conventions are not ratified.

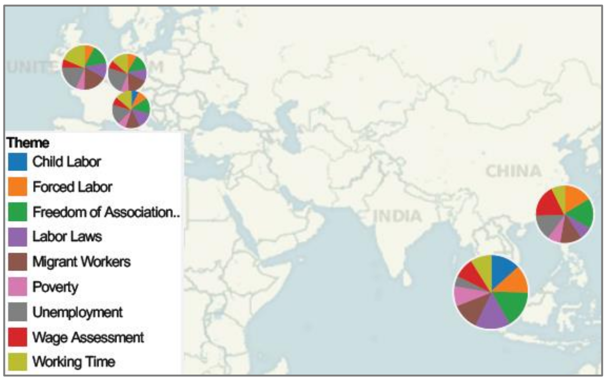


Figure 7 : Social impacts in the category labor rights

(Netherland is for space reasons not displayed but is comparable to UK results) [22]

For the European countries one of the main impacts is the risk of unemployment per sector, which is likely to be increased in the last years due to the crisis and affecting especially Italy in the southern part of Europe [27].

5 DISCUSSION

The results display clearly that there is no black and white answer in assessing sustainability. The alternative performing better in one dimension might perform worth in another one. Furthermore, alternatives which seem more environmental friendly or sustainable in the beginning can show the opposite when having a closer look.

Both were shown in the Pedelec study presented here. Whereas the Eco Pedelec performs slightly better in the environmental dimension, it is much more cost effective on the economic dimension. In addition parts like the titanium frame were assumed to be more environmental friendly, but displayed the complete difference.

Even harder is the assessment of the social impacts, as a clear answer of what to be preferred is hard to find, because even if e.g. the production in Taiwan has negative impacts a lot of workers depending on that industry to finance their livelihoods.

Some uncertainties due to data quality and data availability were recognized during the study. Whereas the LCA data are relatively assured, as actual databases and specific processes are available, in particular the sLCA data have an intrinsic uncertainty. The used database was updated last in 2008 and some changes might have been occurred meanwhile, but data were completed by use of additional sources. Further the sLCA data are only available on a country level; so that no conclusions can be drawn for the considered part of industry or a specific company.

6 CONCLUSION AND OUTLOOK

It has been shown that retrospective methods for assessing sustainability are at an early stage reasonable and needed to support prospective methods to develop in the right direction. It seems possible to create a more sustainable solution based on the findings within both methods. Proposed criteria on an early stage can be the presence of labor laws (e.g. the implementation of the ILO conventions) for the social dimension, price regulations based on the targeted country and group for the economic dimension and the reduction of environmental impacts (e.g. Primary Energy Demand) for the environmental dimension.

Some parts in the Life Cycle Sustainability Assessment still need to be improved. Exemplary can be named the social dimension, where a clearer definition of the main targets seems to be necessary. Also the LCC needs improvements with regard to the impact level.

In next steps the study will be improved by gathering additional data especially for the social and economic dimension. Further the already made findings will be taken into account for the improvement of the Sustainable Product Development.

7 ACKNOWLEDGMENT

We acknowledge that the study is funded by the German Research Foundation DFG (SFB 1026/1 2012), Collaborative

[2] Please note that the labor costs are allocated to the functional unit, which means only the working time needed for one Pedelec is accounted.

Research Center CRC1026 (Sonderforschungsbereich SFB1026).

REFERENCES

[1] United Nations, “Report of the World Commission on Environment and Development - Our Common Future,” 1987.

[2] M. E. Bouwman and H. C. Moll, “Environmental analyses of land transportation systems in the Netherlands,” *Transportation Research Part D: Transport and Environment*, vol. 7, no. 5, pp. 331–345, Sep. 2002.

[3] N. Manthey, H. Neupert, and A. Budde, “GoPedelec.” Wien, pp. 1–84, 2012.

[4] T. Lewis, C. Edegger, and Schriefl E., “Pedelecs and Renewable Energy.” 2012.

[5] European Union, “DIRECTIVE 2002/24/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL,” no. 2002/24/EC. Official Journal of the European Communities.

[6] L. Sheldrick and S. Rahimifard, “Evolution in Ecodesign and Sustainable Design Methodologies,” in *Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013*, 2013, pp. 35–40.

[7] P. Knight and J. O. Jenkins, “Adopting and applying eco-design techniques: a practitioners perspective,” *Journal of Cleaner Production*, vol. 17, no. 5, pp. 549–558, 2009.

[8] G. May, M. Taisch, and E. Kerga, “Assessment of Sustainable Practices in New Product Development,” in *Advances in Production Management Systems. Value Networks: Innovation, Technologies, and Management*, vol. 384, J. Frick and B. T. Laugen, Eds. Berlin and Heidelberg: Springer Berlin Heidelberg, 2012, pp. 437–447.

[9] European Commission, *Making sustainable consumption and production a reality: A guide for business and policy makers to Life Cycle Thinking and Assessment*. 2009.

[10] S. Evans, T. A. Bhamra, M. Simon, T. C. McAloone, S. Poole, and A. Sweatman, “Integrating Environmental Decisions into the Product Development Process: Part 1 Early Stages,” no. September. 1998.

[11] T. A. Bhamra, S. Evans, M. Simon, T. C. McAloone, S. Poole, and A. Sweatman, “Integrating Environmental Decisions into the Product Development Process: Part 1 The Early Stages,” in *First International Symposium On Environmentally Conscious Design and Inverse Manufacturing, EcoDesign ’99*, 1999, pp. 329–333.

[12] ISO, *ISO 14044*. Deutsche Norm, 2006.

[13] ISO, *ISO 14040*. Deutsche Norm, 2006.

[14] W. Klöpffer and B. Grahl, *Ökobilanz (LCA): Ein Leitfaden Für Ausbildung und Beruf*. John Wiley & Sons, 2009, p. 56.

[15] D. Hunkeler, G. Rebitzer, and K. Lichtenvort, *Environmental Life Cycle Costing*. CRC Press, 2008.

[16] T. E. Swarr, D. Hunkeler, W. Klöpffer, H.-L. Pesonen, A. Ciroth, A. C. Brent, and R. Pagan, “Environmental life-cycle costing: a code of practice,” *The International Journal of Life Cycle Assessment*, vol. 16, no. 5, pp. 389–391, Apr. 2011.

[17] C. Benoit and B. Mazijn, Eds., *Guidelines for social life cycle assessment of products*. UNEP/SETAC Life Cycle Initiative, 2009.

[18] M. Finkbeiner, E. M. Schau, A. Lehmann, and M. Traverso, “Towards Life Cycle Sustainability Assessment,” *Sustainability*, vol. 2, no. 10, pp. 3309–3322, Oct. 2010.

[19] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, “ReCiPe 2008,” 2009.

[20] R. K. Rosenbaum, T. M. Bachmann, L. S. Gold, M. a. J. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H. F. Larsen, M. MacLeod, M. Margni, T. E. McKone, J. Payet, M. Schuhmacher, D. Meent, and M. Z. Hauschild, “USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment,” *The International Journal of Life Cycle Assessment*, vol. 13, no. 7, pp. 532–546, Oct. 2008.

[21] C. Benoît, G. a. Norris, S. Valdivia, A. Ciroth, A. Moberg, U. Bos, S. Prakash, C. Ugaya, and T. Beck, “The guidelines for social life cycle assessment of products: just in time!,” *The International Journal of Life Cycle Assessment*, vol. 15, no. 2, pp. 156–163, Jan. 2010.

[22] “Social Hotspot Database,” 2013. [Online]. Available: http://socialhotspot.org/home-about-shdb/. [Accessed: 03-May-2013].

[23] C. Luttropp and J. Lagerstedt, “EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development,” *Journal of Cleaner Production*, vol. 14, no. 15–16, pp. 1396–1408, 2006.

[24] M. R. M. Crul and J. C. Diehl, “Design for Sustainability: A practical approach Developing Economies a practical approach for Developing Economies.” Paris, 2006.

[25] ILO, “LABORSTA Internet (E),” 2010. [Online]. Available: http://laborsta.ilo.org/. [Accessed: 03-May-2013].

[26] SweatFree, “Non-Poverty Wages for Countries Around the World.” [Online]. Available: http://www.sweatfree.org/nonpovertywages. [Accessed: 03-May-2013].

[27] Statista, “• Italy - Unemployment rate 2013 | Statistic,” 2013. [Online]. Available: http://www.statista.com/statistics/17316/unemployment-in-italy/. [Accessed: 03-May-2013].

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

17.6 Openness as a supportive paradigm for eco-efficient Product-Service Systems

J. Bonvoisin[1], J. Wewior[1], F. Ng[2], G. Seliger[1]
[1] Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany
[2] J C Bamford Excavators Limited, Lakeside Works, Rocester, Staffordshire, ST14 5JP, United Kingdom

Abstract
Product-Service System (PSS) is a concept which can be exploited to increase the eco-efficiency of value creation. It does not focus only on physical products but also on common access to their functionality, thus allowing mutualizing of products between manufacturers and users. However, reaching PSS eco-efficiency requires facing the challenge of an intensive information exchange between them. Especially in the case of business-to-consumer offers, stakeholders are an anonymous crowd of users, of which product usage information is hard to be obtained. This paper explores the potential of the Open Design concept - the opening of the development process and its documents - in order to address this problem. By promoting user involvement, Open Design might bridge the gap between use-related information and the design process – thus supporting eco-efficient PSS design. This general idea will be illustrated by the examples of PSS taken from both business-to-business and business-to-consumer domains.
Keywords:
Open Design; Product-Service Systems (PSS); eco-efficiency.

1 INTRODUCTION

It is an often quoted challenge that the eco-efficiency of products shall be increased by more than a factor of ten in order to reconcile economic development with the conservation of the natural capital. To face this challenge, significant efforts have been made by engineering scientific communities within the development of ecodesign, i.e. methods to introduce the environmental dimension into product design (e.g. [1-2]). However, despite of the promising progress these methods were addressing, it still remains unlikely that eco-efficiency of products and services can be increased by a factor of ten. Focusing on products and processes remains limited if consumption patterns remain disregarded at the same time [3].

The focus on the consumption patterns in engineering sciences can be achieved by addressing business models, i.e. how value is created by the interaction of value creation factors (products, processes, organisation, utilities and organisation). In recent years, a wave of innovative business models brought two concepts with interesting potentials for sustainable value creation: Product-Service Systems (PSS) and Open Design.

This paper aims to underline the common advantages of these two concepts and their potential synergies. Furthermore, it studies how Open Design can be used to support the operation of eco-efficient Product-Service Systems, with the help of two concrete examples from the field.

In section two, we highlighted the respective potential advantages of both concepts for sustainable value creation as well as their similarities. In section three, we explored the potential contribution to Open Design for eco-efficient Product-Service Systems before concluding on our reflections in section four.

2 INNOVATIVE BUSINESS MODELS

In this section, we highlighted the potentials of Open Design and Product-Service Systems for sustainability, identify their similarities and define their possible synergies.

2.1 Product-Service Systems

In the past decades, an increasing number of companies shifted their focus from product to customer satisfaction, thus opening opportunities in the offering of innovative solutions to satisfy customer needs. This shift in focus promotes the idea that customer cannot be fully satisfied through merely the purchase of goods, but rather by providing access to better functionalities and services.

Business models implementing this shift can be classified under the name of Product-Service Systems (PSS) – a phrase that describes an integrated offer of products and services aiming at customer satisfaction. By renouncing to focus exclusively on the product, PSS gives the potential to fulfil customer’s needs in an innovative manner, to decrease resource consumption, to intensify the relationship between providers and customers, and thus to offer services that better fit the customer’s demands.

More than describing a unique reality, this umbrella-concept covers a high diversity of business models. Tukker [4], for example, distinguishes eight types of PSS according to the intensity of the relationship between customers and providers and to the respective part of the value-added offered through products and services (table 1). Based on this, he named three categories of PSS depending on what is on the focus of the commercial exchange: the product-itself, its use or the result it provides.

As PSS opens opportunities for innovative solutions to satisfy customer’s needs, it has been argued that PSS has a

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

potential for conciliating economic value creation and preservation of the environment, thus addressing the ecological dimension of sustainability. Therefore, many proposed definitions of PSS include clear references to the environment, such as this often-cited one: "product(s) and service(s) combined in a system to deliver required user functionality in a way that reduces the impact on the environment" [5]. However, several authors call for a better systematic study of the environmental friendliness of PSS, stating that they are not automatically eco-efficient (e.g. [5-6]), notably due to the fact that the term PSS covers a broad range of business models. Nonetheless, it is already widely accepted that PSS show several interesting environmental potentials - especially the use and result oriented ones, as presented hereafter.

Use-oriented models like product sharing may have the following advantages [3, 7]:

- Long product service time, through the design, production and use of reliable and long-lasting products and through maintenance and upgrade;
- Extended producer responsibility, encouraging the take back of products, reuse, remanufacturing, recycling;
- Reduced number of products required to fulfil customers' needs.

Result-oriented services, through internalization of all product-related costs (including use), may have the following advantages [3, 6, 8]:

- Natural incentive to reduce total lifecycle costs, including environmental impacts, operating a natural selection of the most efficient solutions;
- Professional use of products, ensuring lower energy consumption and better care.

Product-oriented services	Product-related service
	Advice and consultancy
Use-oriented services	Product lease
	Product renting or sharing
	Product pooling
Result-oriented services	Activity management/outsourcing
	Pay per service unit
	Functional result

Table 1 - The eight types of PSS according to Tukker from value mainly in product content at the top down to value mainly in service content [4].

2.2 Open Design

The concept of Open Design derives from the extension of the open source movement – originating from software development – to the design of physical products. It refers to "the openness of all accompanying documents in a product development processes, with the aim of collaborative development of tangible objects" [9]. This implies on the one hand that product definition is considered as a common and follows the four principles of the open software philosophy (right to see, use, modify and redistribute). Yet, the design process is no longer considered as the activity of a defined team agreed on confidentiality, but is on the contrary open for the participation of an undefined crowd of interested people. As a consequence, product development cannot be seen any more as a defined project with clearly defined inputs, outputs and timeline, but rather as an on-going process of continuous improvement by a *community* of interested people.

Open Design (as well as open software) can be considered as "an innovative form of production based on a new conception of copyright, a decentralized organization of work, voluntary work and user involvement" [10]. The potential advantages of Open Design are the following [11, 12]:

- Better quality of designs due to higher number of peer reviews;
- Reduced R&D costs and development time due to the involvement of a higher number of (voluntary) contributors;
- Faster innovation and adoption of the latest technologies.

Like PSS, the concept of Open Design is more of a composite figure characterising different concrete situations than a solid representation of a unique reality. The term Open Design can apply to a wide range of design processes and some of these processes are still currently being invented as Open Design is a relatively new concept. Examples of these are "Living Labs", e.g. the physical meeting of several actors of the same product lifecycle in order to identify improvement potentials. Another example would be the publication of product definition documents by their original equipment manufacturers (OEMs) on the internet in order to motivate spontaneous improvement propositions from any interested contributor.

Beyond this diversity, there are two fundamental rules for Open Design: do-it-yourself and mutualisation of knowledge. Open Design promotes the independence of the users to the technology, in reaction to the passivity of the consumer behaviour in mass production. It also promotes reciprocity and mutual learning, giving a progressive meaning to this movement [10]. Under this viewpoint, Open Design questions the relationship between people and factors of production and can be viewed as a potential contribution to the social dimension of sustainable value creation.

2.3 Similarities between the concepts

Beside their respective complementary potential contributions to sustainability (illustrated by figure 1), PSS and Open Design business models show several striking similarities:

- Both take part in a general trend to shift from mass production to mass customization, which tends to consider consumers less as passive buyers with predefined standard needs than as demanding customers with specific requirements.
- Both of them propose a redistribution of the roles between stakeholders in value creation: providers and customers are involved in a process of co-creation where the consumer becomes a "prosumer" and the provider's role is more to propose value than to propose products.
- Both tend to redefine the timeframes of product lifecycles. In PSS business models, the economic exchange is no longer a punctual meeting of self-serving actors on a market, but a long term relationship. In Open Design, product development is less project-oriented (with focus on precise results, starting and ending dates) than process-oriented (with focus on a precise activity).
- Both propose a redefinition of the concept of ownership. Many of the PSS business models provide products for free. In Open Design, it is the product information that is free (which does not imply that the product is also for free).

- For the two of them, this can be either considered as a "commercial suicide" [12] or the opportunity to move to more innovative business models and to differentiate from the competition.

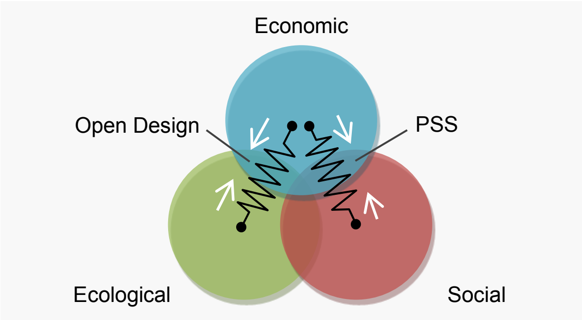


Figure 1 – Complementary contributions of PSS and Open Design to the dimensions of sustainability.

With respect to these similarities and complementarities, it could be insightful to study the potential synergies that exist between these two concepts. For example:

- Development of product-oriented business-models (e.g. advice, consultancy) on the basis of an open design product;
- Manufacturing of open design products in service-oriented business models like MAAS (Manufacturing As A Service) [13] or professionalized FabLabs [14];
- Deeper integration of the customer in the co-creation process of PSS through its participation in design.

3 OPEN DESIGN AS A SUPPORT FOR PSS

In this section, we attempt to study the possible contribution of Open Design as a supportive paradigm for Product-Service Systems. We start to identify challenges appearing in the concept of PSS. We then present two case studies from both the B2B and B2C domains that illustrate these challenges. For each of them, we propose a possible implementation of Open Design solutions.

3.1 Two challenges: understanding and motivating

Shifting to PSS still remains a challenge. Especially for use and result oriented PSS, this implies a strong cultural change on both customer and provider sides [5]. The customer has to renounce on the ownership of the product. The provider has to accept to let the user in taking a larger role in value creation. At the end, both parties should agree on a co-production process, rather than a punctual property exchange.

Particularly on the provider's perspective, this relationship of co-creation brings additional uncertainty into the business model [15]. Additionally, it should be considered that customers are not only interested in the use of products but also on their ownership, which reflects social status and self-esteem [16]. Therefore, customer behaviour may be motivated by other criteria than rationality and eco-efficiency. This fact is representing a threat for the objective of eco-efficiency of PSS.

Consequently, customer behaviour has a critical influence on both the environmental and the economic performance of PSS [16]. This raises the following two challenges of the design and operation of PSS:

- Understanding the user behaviour in order to design efficiently both tangible (e.g. products) and intangible (e.g. maintenance service) elements of the PSS;
- Encouraging the users to efficiently operate the usage phase of tangible elements.

These challenges have already been highlighted by Mont and Plepys [16], particularly for the B2C domain, who pledged for a better understanding of the customer satisfaction in PSS business models through the use of tools close from user centred design like surveys, focus groups or observation. Despite the indisputable contribution to these methods, they remain difficult to operate in daily practice. Customer surveys, for example, are good opportunities to make suggestions on both products and services, but are still not common practice across the industry [17].

At the same time, Open Design provides an opportunity to create a sense of ownership and belonging through the involvement in the design process. On one side, one can develop a sense of ownership through the participation in the birth of a product. On the other side, through this participation, one can get the feeling of belonging to a community. "This product is mine, not in the sense that I own it, but because I participated in its creation. I am also part of a community of the people that participated in this creation".

In the following sections, we present two examples of PSS illustrating both the challenges of motivating and understanding the customer. For each of them, we present a potential answer based use of Open Design. The first example is taken from the B2C domain. It illustrates the need to motivate the user for a more careful use of the product in order to reduce downtimes. The second example is taken from the B2B domain. It illustrates the need of getting use-related information to improve maintenance.

3.2 B2C domain – Rent a bike service

Métrovélo is a rent-a-bike service offered by the city of Grenoble, France. It is delivered by a shared public/private organisation that maintains since 2004 an ever growing pool of more than 3500 bikes that can be rented for a duration spanning from one day to one year. The service encounters an interesting success: since its beginning, more than three millions of renting days have been registered, meaning that the well recognizable yellow bikes are now a part of the local culture (figure 2).

Métrovélo PSS offers

This service belongs to the use-oriented PSS class of Tukker's [4] classification: the product is still in the focus of the commercial exchange, but there is no exchange of ownership (the user does not own the product after the commercial exchange). More precisely, this is a pay-per-access service (in opposition to pay-per-use): users pay for a certain time of access to the product, whatever may be the number of kilometre they ride.

Métrovélo provides three different offers:

- Renting from agencies: the activities of picking the bike up and giving it back are performed in an agency with the help of an employee. The duration of rental contracts can span from 1 day to 1 year. This offer represents the highest share of the activity of the organisation.
- Automatic renting: the activities of picking the bike up and giving it back are performed through an automatic rental system. The rental fee is accounted on an hourly basis.

- Bike pool renting: Métrovélo provides dedicated bike pools for companies who want to offer their employees the possibility to use bikes in their daily trips.

Each of these offers includes the maintenance of the bikes: in case of failure, each customer can come to a Métrovélo agency to have his bike fixed. If a repair cannot be made within a reasonable time frame, the customer is provided with a functional bike waiting in the stock.

Figure 2 - The easy recognizable yellow "Métrovélo" – (Credits: SEMITAG - P. Paillard).

On the relevance of use behaviour

Thanks to the provision of three different servicing conditions, Métrovélo understands the level of motivation customers have in taking care of the product would influence the maintenance requirements (in its frequency and the seriousness of the performed repairs). This experience allows deriving the main influencing factors of the customer behaviour:

- The length of the rental, that allows the establishment of a psychological relationship between the user and the product (feeling of ownership), and let the user be more experienced with the use of his bike (as a consequence, the ratio between the time the product is used by an inexperienced person and the time it is used by an experienced person is reduced).
- The existence of a direct face-to-face relationship between the renter and the user, which tends to reinforce the customers' feeling of responsibility.

These factors are illustrated by the intensity of the maintenance for the three different services offered by the organisation:

- Renting in an agency. In this most favourable case, most bikes are rented for a long period of time (e.g. 3 months or one year) and a direct face-to-face relationship is led between the renter and the customer. In this case, downtime rates are low.
- Bike pool renting. In this less favourable case, the customer is not the user, meaning that there is no direct contact between the owner of the bike and the user. Moreover, bikes are solely taken out of the pool for short trips. Downtime rates in this case are higher than in renting from agencies.
- Automatic renting. In this least favourable case, there is no contact between the user and the renter, and bikes are rented for short trips. Currently, Métrovélo is unsure on the customers' behaviours for this service, especially as additional preventive maintenance is performed on these bikes. Other organisations delivering automatic renting of bikes however witness of significantly high downtimes rates due to misuse (as illustrated for example by Amaya et al. [18]).

Scenario of Openness

Bikes are relatively simple and mature products beneficiating mankind for more than a century. In the case of bike renting, bikes are designed to be robust and not particularly high tech. Consequently, these products can be easily reverse-engineered and intellectual property is not a crucial element within the business model. Therefore, giving access to product definition documents does not represent a threat to the organization.

The product design could be held available for consultation and modification on an Open Design platform, where users could propose design improvements. Firstly, this could help benefit from a continuous improvement of the product design at a lower cost. Secondly, this could help reinforcing the idea of a community of users, and give more affective value to the yellow bikes. Thirdly, this could provide an opportunity to offer new services like customization. Customers can design customized add-ons on the platform. These add-ons could be produced by the service-provider and disseminated through a social network-like feature of the platform. Finally, this could promote qualification of customers and offer them the opportunity to be active also on the maintenance, thus extending the do-it-yourself logic from design to maintenance. Beyond these benefits, the challenge is to make users feel responsible for products they do not own. Especially, products being used for short durations may be handled with low care, and therefore may have a lower environmental performance. Letting users to voice their needs directly in design stage can create a feeling of ownership promoting a sense of responsibility towards the use of products.

The presented solution may however raise several new questions, e.g.:

- To what extent would the users participate in the open design platform?
- How to set up a platform that can manage the contribution of several anonym contributors to the product definition (like an open version of product lifecycle management)?
- How to manage the diversity of products generated by the continuous improvement and the customization in a service where the maintenance efficiency is based on the homogeneity of products?

3.3 B2B domain – Machinery industry

J C Bamford Excavators Ltd (JCB) is one of the world's top three construction equipment manufacturers. JCB produces a variety of over 300 machines sold into construction, agriculture, waste and recycling as well as power generation industries. It was founded by Joseph Cyril Bamford in 1945 in Uttoxeter, Staffordshire, UK. Since then, JCB has expanded to 22 factories on 4 continents and has over 750 dealers worldwide. In May 2013, JCB marked the production of the company's one millionth machine, with nearly one out of every two backhoe loaders sold today being a JCB.

JCB PSS offers

As a manufacturer, JCB also provides the support for spare parts and services to their dealers to care for their customer's machines [17]. The service offered to dealers by JCB belongs to the product-oriented PSS class of Tukker's classification.

On board telemetric data collects use-phase information to generate the requirement of services during or at the end of operational periods. Based on the level of usage, JCB will coordinate with their dealer's service technicians and provide necessary information, service parts or technical support.

JCB offers different service packages to the dealers at the point of sale to suit different dealer's targeted markets.

- Service Agreement: The flexibility for customers to set up a service agreement at the time of purchase, allows the planning and managing of the machine maintenance budget. Service intervals can be based on engine hours / fixed time.
- JCB Premier Cover: 5 Years maximum period or 10,000 engine hours of cover from the date of purchase. Repair and replace defective components in the machine. Machines are also regularly serviced by approved JCB dealers.
- Full repair and Maintenance: Regular maintenance and repairs conducted by JCB dealers with a fixed sum per month. Covers machines up to 5 years or 10,000 engine hours usage.

The effectiveness of these service packages heavily relies on the amount of accurate use-related information being collected and used to determine the needs and requirements at the service intervals.

Figure 3 - Typical Service Support (Credits: JCB).

On the relevance of use-related information

Gaining precise use-related information helps defining realistic use scenarios that can in turn support the definition of reliable preventive maintenance programs. At the end, it helps to reduce downtime and the severity of the problems occurring on machines. This information could also be used for further product improvement. It is, however, difficult to get precise and relevant information on the level of usage. Three sources are currently being used: getting information from the machine (telematics), servicing (investigation during maintenance), or the customer/user (questionnaire).

Telematics. The machines are equipped with sensors and electronics that record activities of the machines (e.g. pressure and proximity switches). This information can then be collected during maintenance.

These systems can be costly but justified to reduce machine downtime: the end of life of components can be accurately predicted and a replacement of such components can be scheduled in before failures materialised.

Due to current technological limitations and the availability of space on machines, captured information is likely to be insufficient to generate a full picture of the machine usage. Furthermore, some construction machines are designed to perform various numbers of different jobs/duties (>25), as a result, identifying these duties using sensors will require sophisticated algorithms.

The advantage of telematics is thus limited, and more technical solutions may be required.

Diagnostic during maintenance. When searching for the root cause of a technical problem, assumptions tend to be made. It can be difficult to make an accurate diagnosis without a full picture in how the machine has been used. Generally, service technicians take the forensic approach by searching for symptoms, such as slow service speeds and internal hydraulic leakage.

Consulting with the customers. Direct communication with the customers is considered the easiest way to gather important evidence. Yet the process can be time consuming, and customers may not always tell the truth. Furthermore, customers may not be the end-user, who will not be able to provide any useful information but inaccurate personal assumptions/evaluations.

Scenario of Openness

On this example, product design and technical innovation is a key factor within the business model of the company. Giving access to the product definition thus implies non negligible risks. To avoid this pitfall and to benefit from the users' experience, a softer version of Open Design could be used, like a Living-Lab approach: a meeting of actors of the product lifecycle that try to generate ideas for product improvement. OEMs could set up global exchange conferences, where dealers, customers and end-users were invited to contribute with their personal experiences and suggestions to the design and development of new and current products. Discussion groups can be divided by a particular machine type, and chair by an engineer of the particular specialty. Such events would promote discussions based on the actual needs and requirements from the customers/end users, breaching the barriers of between all parties.

Another solution is to let the users formulating ideas directly from the place they may appear, i.e. the workplace. On-board solutions could be used for this purpose – e.g. embedded computer with touchscreen (to make quick drawings) and a voice recorder (to express ideas directly as they appear).

These solutions may however raise several questions, e.g.:

- To what extent would be the users ready to participate and express their ideas/comments?
- How to design an ergonomic on-board solution helping the user expressing ideas in a form that is usable by product designers?
- How to design a system for on-board solution that would be accepted by users and freely used?

4 CONCLUSION & OUTLOOK

In this paper, we made the first attempt to identify potential synergies between PSS and Open Design ways of thinking. The arguments in this paper suggested that both concepts are following a common trend, sharing many characteristics and can bring complementary answers for the design of sustainable business models.

However, associating these two complicated concepts may raise more questions than providing answers. For example, it seems that this association is more relevant (or at least easier to implement) for the B2C domain than for the B2B domain (because in this last case, the user and the contractor are not the same person). Some aspects of the two concepts may also seem contradictory: how to conciliate the trend of systematic outsourcing proposed by the PSS logic with the also systematic do-it-yourself thinking proposed by the Open Design logic? Is a deeper integration of the actors of the product lifecycle and an ever decentralised design compatible?

The aim of this paper is therefore not to derive new concepts and nor to participate in the explosion of fragile and inapplicable concepts, but, to identify common characteristics that can give ideas for sustainable product and service offers. The first theoretical reflections presented here shall be followed by implementations and critical analysis of concrete examples, that we hope these first reflections will motivate. (Open) work in progress…

5 ACKNOWLEDGMENTS

The authors would like to thank Alain Montillier (Métrovélo) and Jörg Wimalasena for their precious contributions in this paper.

6 REFERENCES

[1] Abele, E., Reiner, A., Birkhofer, A., 2004, *Environmentally-Friendly Product Development: Methods and Tools*, Springer.

[2] Brissaud, D., Tichkiewitch, S., Zwolinski, P., 2006, *Innovation in Life Cycle Engineering and Sustainable Development*, Springer.

[3] Meijkamp, R., 1998, Changing consumer behaviour through eco-efficient services: an empirical study of car sharing in the Netherlands, *Business Strategy and the Environment*, 7/4:234-244.

[4] Tukker, A., 2004, Eight types of product–service system: eight ways to sustainability? Experiences from SusProNet, *Business Strategy and the Environment*, 13/4: 246-260.

[5] Baines, T. S., Lightfoot, H. W., Evans, S., et al., 2007, State-of-the-art in product-service systems, *Proceedings of the Institution of Mechanical Engineers: Part B Journal of Engineering Manufacture*, 221/10:1543-1552.

[6] Lingegard, S., Sakao, T., Lindahl, M., 2012, Integrated Product Service Engineering - Factors Influencing Environmental Performance, *Systems Engineering - Practice and Theory*, Cogan B. (ed.), InTech.

[7] Intlekofer, K., Bras, B., Ferguson, M., 2010, Energy Implications of Product Leasing, *Environmental Science and Technology,* 44/12:4409-4415.

[8] Pigosso, D., Is the Industrial Product-Service System really sustainable? 2010, presented at the 2nd CIRP IPS² Conference, Linköping, Sweden.

[9] Geyer, M., Reise, C., Manav, F., *et al.*, Open design for manufacturing – Best practice and future challenges 2013, presented at the 10th Global Conference on Sustainable Manufacturing (GCSM 2012).

[10] Depoorter, G., 2013, La “communauté du logiciel libre” : espace contemporain de reconfiguration des luttes? in *Résister Au Quotidien ?* Frère, B., Jacquemain, M. (eds.), Presses de Sciences Po, Paris.

[11] Buitenhuis, A. J., Pearce, J. M., 2012, Open-source development of solar photovoltaic technology, *Energy for Sustainable Development*, 16/3:379-388.

[12] Howard, T. J., Achiche, S., Özkil, A., McAloone, T. C., 2012, Open Design and Crowdsourcing: maturity, methodology and business models, in *Proceedings of the 12th International Design Conference DESIGN 2012*, 181-190.

[13] Yip, A.L.K., Jagadeesan, A.P., Corney, J.R., et al., 2011, A Front-End System to Support Cloud-Based Manufacturing of Customized Products, in: Harrison, D.K., Wood, B.M., Evans, D. (Eds.), *Advances in Manufacturing Technology XXV - Proceedings of the 9th International Conference on Manufacturing Research ICMR 2011*, 193–198.

[14] Gershenfeld, N.A., 2007. *Fab: the coming revolution on your desktop--from personal computers to personal fabrication*. Basic Books, New York.

[15] Seiringer, W., 2013, A Rating for Customer Participation during the Process of Service Co-creation, in *Product-Service Integration for Sustainable Solutions*, H. Meier (ed.), Springer, 647-658.

[16] Mont, O., Plepys, A., 2003, *Customer satisfaction: review of literature and application to the product-service systems - Final report to the Society for Non-Traditional Technology, Japan*.

[17] Ng, F., Harding, J., Rosamond, E., 2013, A Customers' Satisfaction Based Framework for Continuous Development of PSS, in *The Philosopher's Stone for Sustainability*, Shimomura, Y., Kimita, K. (eds.), Springer, 239-244.

[18] Amaya, J., Lelah, A., Zwolinski, P., 2013, Environmental Benefits of PSS Strategies: A Bicycle Sharing System Case Study," in *The Philosopher's Stone for Sustainability*, Shimomura, Y., Kimita, K. (eds.), Springer, 339-344.

17.7 A System Dynamic Enhancement for the Scenario Technique

A. Brose[1], A. Fügenschuh[2], P. Gausemeier[1], I. Vierhaus[3], G. Seliger[1]
[1] Institut für Werkzeugmaschinen und Fabrikbetrieb, Berlin, Germany
[2] Helmut Schmidt University / University of the Federal Armed Forces Hamburg, Germany
[3] Department Optimization, Zuse Institute Berlin, Germany

Abstract:
The Scenario Technique is a strategic planning method that aims to describe and analyze potential developments of a considered system in the future. Its application consists of several steps, from an initial problem analysis over an influence analysis to projections of key factors and a definition of the scenarios to a final interpretation of the results. The technique itself combines qualitative and quantitative methods and is an enhancement of the standard Scenario Technique. We use the numerical values gathered during the influence analysis, and embed them in a System Dynamics framework. This yields a mathematically rigorous way to achieve predictions of the system's future behavior from an initial impulse and the feedback structure of the factors. The outcome of our new method is a further way of projecting the present into the future, which enables the user of the Scenario Technique to obtain a validation of the results achieved by the standard method.

Keywords:
Scenario Technique; System Dynamics

1 INTRODUCTION

The Scenario Technique is a method for systematically studying a system, and to create consistent scenarios of its future. A scenario is consistent, if it does not contain internal contradictions. According to Garcia [1], a system is defined here as "a set of interrelated elements, where any change in any element affects the set as a whole". Scenarios can be useful to broaden one's view for the various states a future system could take. In this respect the Scenario Technique has proven its value in contexts ranging from business applications to world models, c.f. Chermack et al. [2].

System Dynamics is a method to describe a system (in the sense of Garcia [1]) by stocks and flows, and functional relations between those. The dynamic of the system is governed by feedback loops. Due to the non-linear equation structures it is only possible to analyze the future or long-term behavior of such systems for specially structured and small systems. For realistic and large applications of System Dynamics one applies simulation techniques. Here the current state of the system is projected into the future using the mathematical equations that describe the system. System Dynamics was applied as a tool to understand the behavior of complex systems (for example companies or supply chains) and to develop policies to move the system into a desired state, c.f. Sterman [3].

This paper develops an enhancement of the classical Scenario Technique according to Gausemeier et al. [4]. It replaces some of the steps of the scenario process with steps from the field of System Dynamics. We briefly introduce the two futures techniques, Scenario Technique and System Dynamics, in Section 2. We first explain our new method using a simplified mini-world model of Bossel [5] as an introductory example in Section 3. A concluding summary of our results is provided in Section 4.

2 FUTURES TECHNIQUES

Below we give a brief introduction to the two futures approaches, Scenario Technique and System Dynamics.

2.1 Scenario Technique

Scenario Technique has its origins in the early second half of the 20th century. US-researchers coined the term "scenarios" to describe the potential outcomes of a nuclear confrontation between the two post World War II super-powers USA and USSR [6]. Originating as a military planning tool, the concept of scenarios developed into a business planning tool to help create strategies for the future [7]. Shell Oil started using scenarios in the 1970s to anticipate changes in the market. The oil crises of the 1970s further emphasized the need for prognosis methods that could take structural changes into account [8]. In this context the Scenario Technique developed into a useful instrument, whose main use is to create consistent scenarios and thus broaden the horizon of the minds of decision-makers by presenting them alternative futures, and to make them accept the fact that the future can be vastly different from the present [9]. It helps in identifying future threats and opportunities, so that strategies can be based upon these results. However, the Scenario Technique has its weaknesses. In particular, the system's feedback structure, which is generated by the elements of the system influencing one another, is not analyzed in great detail. What is more, once the scenarios are generated, there is no further information on how exactly to make use of the opportunities and how changes will affect the system. Precisely these aspects are focal points the System Dynamics method for futures studies, to be presented in the next section.

A scenario is defined as a "descriptive narrative of plausible alternative projections of a specific part of the future" [10]. However, when speaking of *the* Scenario Technique, we have to acknowledge that there is actually a great number of different Scenario Techniques [11]. Martelli [12] calls this the "methodological chaos" prevailing in the field of futures studies. We focus here in particular on the methodology of Gausemeier et al. [4]. Below we outline its individual steps. According to the typology of Borjeson et al. [13], the Scenario Technique applied in this paper creates explorative, external scenarios. "Explorative" means the method aims to create several scenarios of possible events set in a distant point in time, allowing a structural change to happen. "External" means only those drivers which are beyond the control of those planning are taken into account.

2.2 System Dynamics

The development of System Dynamics is generally attributed to the MIT Professor Jay W. Forrester. Forrester developed in the 1950s a method of depicting a given system in a simple way, which enabled simulations of the system to be run by computers and the reasons for undesirable system behavior to be identified [14]. His method describes a system using "stocks" and "flows", whereby a stock is an accumulation of something and a flow represents a movement of this something from one to another stock. A flow is normally understood as a movement of stock per time, for example, 2 liters per hour [15].

Forrester states that knowing a system's internal structure is more important towards understanding its behavior than being aware of the external influences affecting the system [14, 15]. This is contrary to most people's and perhaps especially manager's fondness of blaming external drivers beyond their control for bad results or unwanted system behavior in general [1].

The conversion of a real life system into a simulation model can be achieved using Forrester's six step process [16]. In general, this is an iterative process involving much changing and customizing of the preceding steps. The goal of the process is to understand the system, so that unwanted system behavior can be corrected in an appropriate way.

3 DEVELOPMENT OF A COMBINED METHOD

Scenario Technique and System Dynamics were both developed in the USA, roughly at the same time. Both methods have the goal to find an adequate description of what potentially happens in the (far) future. However, the way of achieving this goal is quite different. A combined method would have the advantage of creating consistent scenarios, while at the same time being able to simulate a model's behavior over time. The simulation aspect allows the user to identify what Forrester calls "high leverage policies". These are elements of the system, which have a strong influence on the system's overall behavior when they are changed. Identifying these elements can prevent the typical mistake of trying to change the system's behavior by attacking only the symptoms of an undesirable behavior [14].

3.1 Setting up the model

We describe our attempt to bring together System Dynamics and the Scenario Technique into a combined method. As a test case, we use the mini-world model developed by Bossel [5], which is a simplification of the much more sophisticated World2 and World3 models of Forrester [17] and Meadows et al. [18]. This world model contains three key drivers: consumption C, environmental damage ED, and population P. Bossel simulates this system's behavior using its nonlinear and ordinary differential equations description, but we will proceed with a simulation using only information gained in the scenario process. We assume a linear dynamic of a system with a different set of coefficients for positive and negative components in the state vector

$$x_{t+1} = A^{+}\mathrm{max}_c\left(\vec{0}, x_t\right) + A^{-}\mathrm{min}_c\left(\vec{0}, x_t\right), \quad (1)$$

with the componentwise minimum min_c. An initial impulse $x_0 \in \mathbb{R}^3$ is given. The coordinates of the 3-vectors x_t represent the three key drivers C, ED, P. Below we describe how the entries of the 3×3-matrix A are obtained. The resulting scenarios will be verified by running the system's behavior through the standard scenario process of Gausemeier et al. [4].

For the development of our new method applied to the mini-world system, we made the following assumptions and simplifications:

- The key drivers' only projections are "rises 1%", "sinks 1%", or "remains (more or less) the same".
- The effect of a change in one key driver can have a maximum influence on the other drivers of $\pm 2\%$.
- All effects take place without a time lag.
- Impulses can only cause a $+1\%$, $\pm 0\%$ or -1% change in the key drivers.
- Impulses are unique events, at the beginning of the simulation in $t = 0$.
- There is a linear relationship between the key drivers.

After having made these simplifications, we developed a method which enhances the standard scenario process and adds aspects of System Dynamics thinking. The question is how to set up matrix A from the steps of the scenario process.

To simulate the system's behavior we need to estimate the influence of a change in one key driver on the other drivers. To characterize this influence, we have to be able to identify its magnitude and the direction (as in "$+$" or "$-$") of the influence. The direction of the influence follows from the definition of the key drivers from step 2 of the scenario process. As an initial step, we write down the following matrix, which we call *definition matrix*. It shows the direction of the effect that a change in one key driver has on the remaining key drivers.

definition matrix		C	ED	P
key drivers	change			
C	$+$		direction of "$+$" change in C on ED	
	$-$		direction of "$-$" change in C on ED	
ED	$+$			
	$-$			
P	$+$			
	$-$			

Next we identify the magnitude of the effect on the key drivers by first completing a *direct influence matrix* as in Gausemeier et al. [4] using the scale:

0 = no influence,

1 = slight influence,

2 = medium influence,

3 = strong influence.

direct influence matrix	C	ED	P
C		direct influence of C on ED	
ED			
P			

For what follows, the direct influence matrix cannot be used. To enable us to estimate the strength of the effect of a change in one key driver on the others, we enhanced the direct influence matrix, again making use of the above scale of magnitude. The resulting matrix, the *enhanced direct influence matrix* depicts the magnitude of the reaction of the other key drivers to a $\pm 1\%$ change in one key driver. Due to our simplifications, the possible impulses which effect a change in the key drivers are identical to the key driver's possible projections.

enhanced direct influence matrix		C	ED	P
C	$+1\%$		magnitude of reaction of ED to a $+1\%$ change in C	
	-1%		magnitude of reaction of ED to a -1% change in C	
ED	$+1\%$			
	-1%			
P	$+1\%$			
	-1%			

We now have two matrices, the definition matrix and the enhanced direct influence matrix. The first one contains data on the mathematical direction of the reaction of other key drivers to a change in one key driver, and the second one contains data on the magnitude of this reaction. We connect these two matrices into the *combined matrix*, which is the matrix A that we use for running a simulation of the system. From the simplifications we made, we developed a scale transforming estimations of strength of the reaction into percent (%) changes as follows:

0 = no influence = 0% change,

1 = slight influence = $\pm 0.5\%$ change,

2 = medium influence = $\pm 1\%$ change,

3 = strong influence = $\pm 2\%$ change.

In the case of our mini-world model example [5], the combined matrix thus has the following shape.

combined matrix		C	ED	P
C	$+1\%$		$+1\%$	$\pm 0\%$
	-1%		-1%	-0.5%
ED	$+1\%$	-0.5%		-0.5%
	-1%	$\pm 0\%$		$+0.5\%$
P	$+1\%$	$+1\%$	$+2\%$	
	-1%	-0.5%	-0.5%	

3.2 Running the model

The combined matrix A is split up into the 3×3 matrices A^+ containing only the rows defining reactions to positive impulses, and A^- containing the rows defining reactions to negative impulses. The resulting matrices A^+, A^- are used to simulate the system's reaction to a number of external impulses or "shocks". Setting the value of all the key drivers to 1, these impulses could have an effect of +1%, -1% or no effect on the key drivers. To simulate simultaneous impulses on all the key drivers we defined an impulse vector.

$$x_0 := \text{impulse vector} := \begin{pmatrix} \text{impulse on } C \\ \text{impulse on } ED \\ \text{impulse on } P \end{pmatrix}$$

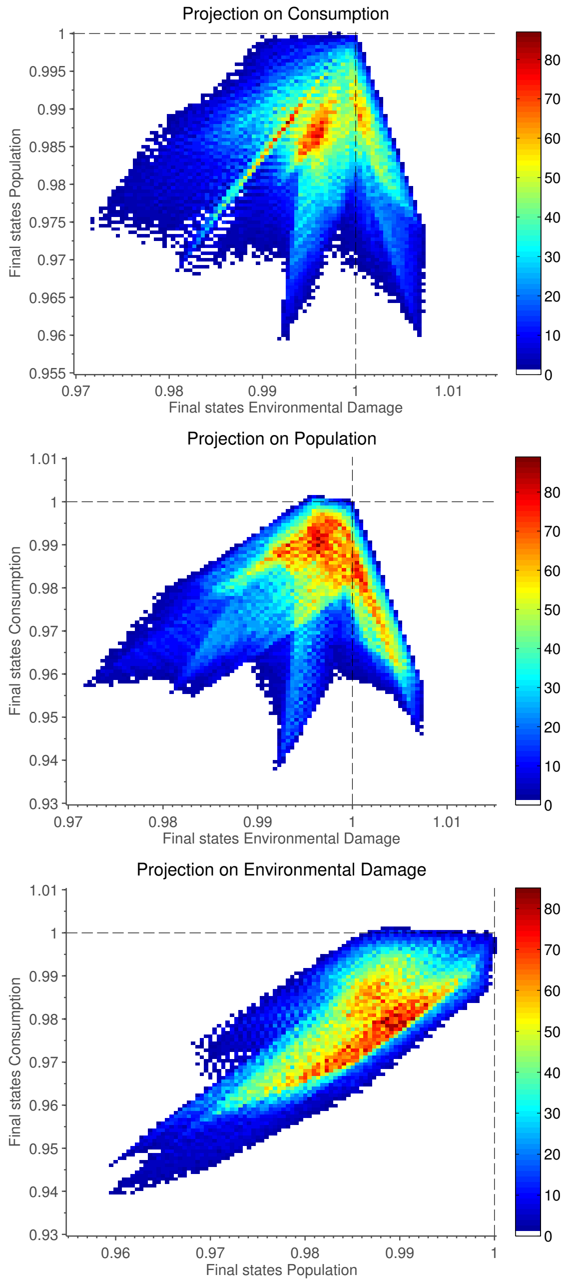


Figure 1: 2D projections of the final state vector space for $68,921$ impulses in $[-1,1]^3$.

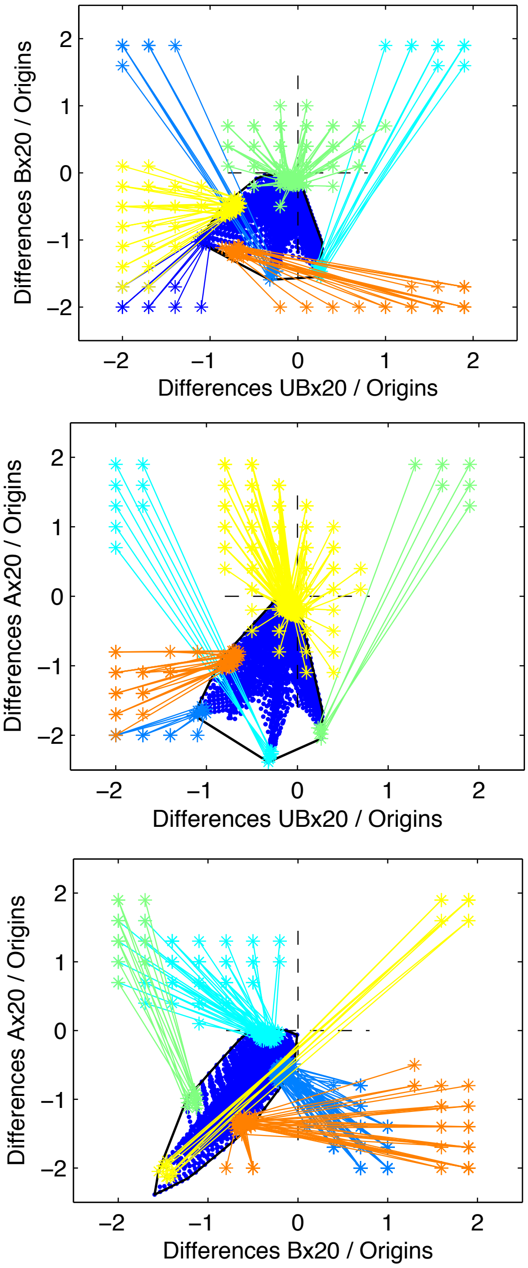


Figure 2: Clustering final state vectors from extremal scenarios.

An impulse vector $x_0 := (1,-1,0)^T$ would thus be interpreted as a positive $+1\%$ impulse of C, a negative -1% impulse of ED and no change of P. This initial impulse is simulated using the model's equation (1) for $t = 0, 1, \ldots$. This is a potentially infinite sequence of vectors x_t, that describe how the initial impulse is distributed through the system's key drivers. Actually, we see that after some iterations this impulse loses its momentum and vanishes, meaning that x_t is converging to the zero vector. For our mini-world data from above, we reached the computer floating point limit after at most 50 iterations.

To estimate the long-term effect of an initial impulse, we ask how the system has changed *because* of this initial impulse. That is, we integrate all intermediate vectors and reach a final *system shift vector* σ:

$$\sigma := \int_{t=0}^{\infty} x(t)dt \approx \lim_{T\to\infty} \frac{1}{T} \sum_{t=0}^{T} x_t.$$

For practical calculations, we evaluate the limit at the point $T = 50$, where the value of x_t has already fallen below computer floating point precision.

If we assume that in the beginning all key factors have a nominal value of 1, then the system is at first described by the *initial state vector* $\alpha := (1,1,1)^T$. Then the *final state vector* of the system is computed as $\Omega := \alpha + \sigma = (1,1,1)^T + \sigma$. For example, the above impulse vector $x_0 := (1,-1,0)^T$ leads in the simulation to $\sigma = (0.2, 0.5, -0.2)^T$, hence the final state of the system is $\Omega = (1.2, 1.5, 0.8)^T$. This means, that the initial impulse of $(1,-1,0)^T$ has a long-term effect on the system, so that C rises to 1.2, ED rises to 1.5 and P sinks to 0.8 units.

Since the model system has three key drivers and an impulse can have one of three effects on each key driver ($+1\%$, -1% or $\pm 0\%$) there are $3^3 = 27$ different impulse vectors. We use a fine discretization for the initial impulse vectors of 0.05 units, which results in $41^3 = 68,921$ different impulse vectors. The resulting final state vectors are be plotted in a graph (see Figure 1), which then allows to pool similar final state vectors to form scenarios (see Figure 2).

We identified six different clusters, depicted by different colors in Figure 2. The straight lines indicate the corresponding impulse vectors that can lead to a final state belonging to some cluster. In some cases there is only a narrow bandwidth for the impulses, and in other cases there is a large variety of different impulses that all lead to a final state in the same cluster.

3.3 Interpretation

The description and interpretation of the resulting scenarios will be omitted here. The mini-world model of [5] was run through the standard scenario process to create a number of consistent scenarios. A comparison of the enhanced method's scenarios and the standard method's scenarios shows us that the scenarios generated by the enhanced method are among those of the standard method which is to say the enhanced method generated consistent scenarios.

The enhanced method has a number of advantages. Whereas the standard method would interpret end values of driver C of $C = 1.01$ and $C = 1.1$ as "driver C rises", the enhanced model enables a more in-depth interpretation of the results. It creates scenarios in which the user can interpret the results of the driver's relative change. In the above example this would be "C rises only marginally" and "C rises drastically". To cover these possibilities, the standard scenario technique would have to define "C rises only marginally" and "C rises drastically" as projections for C, our enhanced technique covers these possibilities, and many others, automatically.

This result raises the question, whether the combined matrix A is able to substitute the consistency matrix with no detrimental effect on the scenario process. After all, both create consistent scenarios and the combined matrix allows a more in-depth interpretation of the resulting scenarios. If this were the case, the consistency analysis could be omitted, which would result in a quicker scenario process. True, instead of the consistency matrix one has to fill in the enhanced influence matrix, but it is usually easier to estimate the influence of one key driver on another than to estimate the consistency of two key driver's projections occurring at the same time.

To answer the question whether the consistency matrix can be replaced by the combined matrix, we must analyze in more depth what exactly each matrix stands for in the scenario process. The consistency matrix contains estimates of how well two projections of different key drivers "fit". By "fit" we mean how likely it is, that when one projection occurs the other will occur at the same time. An example of a highly consistent occurrence would be "rising population and rising environmental damage", an example of an inconsistent occurrence with a low consistency value would be "rising population and sinking environmental damage" (if we accept that more people cause more environmental damage). By estimating how likely various combinations of occurrences are, we are using intuition to evaluate how likely it is for various "blocks" to appear in a scenario. A "block" is a combination of two projections of different key drivers. By doing this for all the combinations of projections, we are forming a network within the system.

The combined matrix also relies on intuition but evaluates how strongly a projection of a key driver influences the remaining key drivers. By doing this, again a network is being created. This network also shapes the scenarios which result from the process. These two networks are "related" in that they both rely on intuition to shape the ties among the key drivers and their projections but they evaluate different aspects of these ties, namely one consistency and the other influence. If we accept that these are two aspects of the same system and that evaluations based on intuition are consistent in the sense that they do not change over time, then it is possible to replace the consistency matrix with the combined matrix.

This then results in a new process for creating scenarios. This process is based on the scenario process according to Gausemeier et al. [4], but is amplified by adding some aspects of System Dynamics.

4 OUTLOOK AND CONCLUSIONS

It is our ongoing research to analyze whether these steps are applicable for other Scenario Technique applications, and how to formulate the initial simplifications and assumptions. Should these be removed, the new method must be slightly altered. Some simplifications are easily removed and even have a positive effect on the simulation by making it more realistic and more dynamic, e.g. including more than three key drivers, incorporating time lag of effects and allowing several impulses to take place over time.

In general, problems arise with the categorization of key driver's projections. Not all drivers can be described numerically in the form of “rises/ falls x%”. For example, how would one interpret “protectionism” as a projection of the key driver “development of global trade”? One possible solution would be to describe these types of key drives qualitatively and simply estimate the strength of this projection and its direction of influence on the other key drivers, limiting the range of maximum effect to the standard $\pm 2\%$. These drivers, which cannot be described quantitatively could thus be integrated into the combined matrix and the simulation. In the same way, impulses of, say $+1\%$ can be interpreted not as “1% more protectionism” but rather “more or stronger developments towards protectionism”. Taking both these adaptations into account, one can incorporate quantitative key drivers into the simulation and the impulses.

This paper laid the foundation for the development of a new scenario technique. The Scenario Technique based on Gausemeier et al. [4] was amplified by adding aspects of System Dynamics into the scenario creation process. This leads to a more in-depth and varied interpretation of scenarios. The new process was developed using a mini-world model consisting of three key drivers. Several simplifications were made during the process. The process was formalized in a step by step instruction. We demonstrated how to apply our new method to a small mini-world example of Bossel [5]. In our future research we aim to apply our new method to a larger Scenario Technique application.

ACKNOWLEDGEMENT

We gratefully acknowledge the funding of this work by the German Research Association (Deutsche Forschungsgemeinschaft, DFG), Collaborative Research Center CRC1026 (Sonderforschungsbereich SFB1026). The second coauthor conducted parts of this research under a Konrad-Zuse-Fellowship.

References

[1] García, J. M., 2009. Theory and Practical Exercises of System Dynamics. MIT Sloan School of Management, Cambridge, MA.

[2] Chermack, T., Lynham, S. A., Ruona, W. E. A., 2001. A Review of Scenario Planning Literature. Futures Research Quarterly, 17(2):7 – 31.

[3] Sterman, J. D., 2000. Business Dynamics – Systems Thinking and Modeling for a Complex World. Irwing McGraw-Hill, Boston.

[4] Gausemeier, J., Fink, A., Schlake, O., 1996. Szenario-Management, Planen und Führen mit Szenarien. Carl-Hanser Verlag, Munich.

[5] Bossel, H., 2004. Systemzoo 3: Wirtschaft, Gesellschaft und Entwicklung. Books on Demand GmbH, Norderstedt.

[6] Campbell, V., 2004. How RAND Invented the Postwar World: Satellites, Systems Analysis, Computing, the Internet – Almost All the Defining Features of the Information Age Were Shaped in Part at the RAND Corporation. Invention & Technology, 20(1):50 – 59.

[7] Millett, S. M., 2003. The future of scenarios: challenges and opportunities. Strategy & Leadership, 31(2):16 – 24.

[8] von Reibnitz, U., 1992. Szenario-Technik; Instrumente für die unternehmerische und persönliche Erfolgsplanung. Betriebswirtschaftlicher Verlag, Wiesbaden.

[9] Cornelius, P., van de Putte, A., Romani, M., 2005. Three Decades of Scenario Planning in Shell. California Management Review, 48(1):92 – 109.

[10] Fahey, L., M., R. R., 1998. Learning from the Future: Competitive Foresight Scenarios. John Wiley & Sons, Hoboken, New Jersey.

[11] Bishop, P., Hines, A., Collins, T., 2007. The current state of scenario development: an overview of techniques. Foresight, 9(1):5 – 25.

[12] Martelli, A., 2001. Scenario building and scenario planning: state of the art and prospects of evolution. Futures Research Quarterly, 17(2):57 – 70.

[13] Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and techniques: Towards a user’s guide. Futures, 38:723 – 739.

[14] Forrester, J. W., 1991. System Dynamics and the Lessons of 35 Years. In K. B. De Greene, editor, The Systemic Basis of Policy Making in the 1990s. MIT Press, Cambridge, MA, 1 – 35.

[15] Kirkwood, C. W., 1998. System Dynamics Methods: A quick introduction. Technical Report, College of Business, Arizona State University, Arizona.

[16] Forrester, J. W., 1994. System Dynamics, Systems Thinking, and Soft OR. System Dynamics Review, 10(2):1 – 14.

[17] Forrester, J., 1973. World Dynamics. Waltham, MA, Pegasus Communications.

[18] Meadows, D., Meadows, D., Randers, J., Behrens III, W., 1972. The Limits to Growth. Universe Books, New York, NY.

GCSM 11th Global Conference on Sustainable Manufacturing
2013 23rd - 25th September Berlin - Germany

17.8 Sustainability analysis for indicator-based benchmarking solutions

H. Kohl[1], R. Orth[1], O. Riebartsch[1]
[1] Department for Corporate Management, Fraunhofer IPK Berlin, Germany

Abstract
In times of scarce resources, the concept of sustainability management has become tremendously important within today's business environment. The integration of a sustainable perspective into corporate management structures does not only satisfy the involved stakeholders, but rather prepares a company to cope with the continuously increasing challenges on the markets. The Fraunhofer Institute for Production Systems and Design Technology (IPK) offers the BenchmarkIndex-Analysis that allows especially small and medium-sized enterprises (SME) to measure their business performance based on selected indicators of the Balanced Scorecard (BSC). Since the methodology and the broad dissemination of the BenchmarkIndex represent a promising opportunity for a wide application of sustainability management solutions, an analysis of existing and potential sustainability indicators was carried out to identify how an adaption of the BenchmarkIndex can consider the long-term economic, but in particular the environmental and social aspects of sustainability.

Keywords:
Benchmarking; Sustainability Management; Triple Bottom Line

1 INTRODUCTION

The behavior and success of enterprises significantly influence the economic, social and ecological situation of our society. On the one side, enterprises generate jobs, products and services to satisfy the needs of the society. On the other side, their value chain processes use up natural, financial and human resources with partly significant (environmental) impacts [1]. As the signs for misbehavior, especially in the form of ecological emaciation in the first and social exploitation in the third world, are increasing, the subject of sustainability has risen to major importance in today's world [2].

Besides the social responsibility towards present and future generations, the application of sustainability is also a self-interested concern for enterprises, since it becomes more and more a factor that is critical to success. Not only consumers and politics demand more corporate transparency regarding this subject, but also financial analysts, rating agencies and investors are increasingly interested in the sustainability profile of enterprises [3]. This development is not at least the result of Basel II, which is the umbrella term for the recommendations on capital reserves within the European Union. It demands a stronger forward-looking risk weighting of credits and therefore more qualitative indicators such as the quality of management relating to sustainability. The modernization directive 2003/51/EG by the EU introduced even a reporting duty on non-financial performance indicators for all DAX companies. As a result, framework conditions on the market have changed [4; 5].

In addition to the economical scarcity, ecological and social scarcities are becoming a central task of corporate management [2]. The consumption of raw materials constitutes the biggest element of costs with about 42% of the total production value [6]. The sense of urgency to use raw materials efficiently rises in accordance to the simultaneous increase in raw material shortage for industry production. Another example is the shortage of skilled labor, which points out the major role of social aspects while coping with scarcities. As a consequence, the operationalization of sustainability includes the pursuing of ecological, economic and social goals as well as the integration of those in the conventional management [3]. Furthermore, the special features of small and medium-sized enterprises (SME) require a differentiated treatment of ecological and social aspects. The limited number of staff and the restricted financial resources in SMEs are only one reason, why environmental management systems are rather deployed in larger companies [1]. Furthermore, the common reporting by big enterprises for their shareholders and supervisory boards is not obligatory for SMEs, because of different ownership structures. As a result, SMEs often don't possess the necessary information and data systems for successful sustainability management [1; 7; 8]. Therefore, those enterprises need simple solutions showing them how to put sustainable business implementations into practice.

The priority objective of this paper is to support decision makers of SMEs in managing the business-relevant ecological and social aspects systematically. The BenchmarkIndex-Analysis allows enterprises to measure their performance on basis of selected indicators and was developed especially for the requirements of SMEs. Since the BenchmarkIndex represents a promising possibility to disseminate sustainability management to a huge customer base of more than 100.000 enterprises, the paper will examine how an extension of the current BenchmarkIndex-Analysis can serve as a tool for the implementation of sustainability management in SMEs.

2 SUSTAINABILITY – A DEFINITION

The following chapter gives an introduction about the macroeconomic significance and interpretation of sustainability followed by a microeconomic approach for the practice-oriented implementation on corporate level.

2.1 The three dimensions of sustainable development

The "World Commission on Environment and Development" has defined the term "Sustainability" in the so called Brundtland Report in 1987: "Sustainable development is development that meets the needs of the present without compro-

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

mising the ability of future generations to meet their own needs” [9].

As a conceptual starting point for the implementation of a sustainable development on economy as well as on corporate level, the distinction in three different dimensions is usual: Ecologic, economic and social [10; 11]. In particular on the corporate level the three-dimensional concept of sustainability is also known by the term “Triple Bottom Line“[12].

The original illustration of this concept is the "3-Pillars Model”. Today the “Sustainability Triangle” is more common, since its three equilateral sides symbolize the equal importance of all elements [13]. The principal of a three-dimensional value creation, demanded by the „Sustainability Triangle“, is based on three types of capital, which need so be sustained [2; 14; 15].

Economic Capital

Economic approaches mostly distinguish between financial capital (e.g. equity and outside capital), real capital (e.g. machines, plants and real estate) and structural capital (e.g. expertise, patents, and management instruments) [2; 16]. The underlying message of this definition implies that enterprises can only contribute to sustainability when they are able to achieve yields on the long-run that are above their expenses in order to secure their financial situation.

Ecological Capital

Ecological approaches distinguish between influencing input and output factors. On the input side, the aim is to use natural resources only within their reproduction capacity or under the development rate of substitutes [2]. In this regard, it is common to distinguish between renewable and non-renewable resources. On the output side, enterprises have to monitor emissions and reduce them, if necessary, in order to preserve ecosystems and their capacity [17; 18].

Social Capital

Considering the social capital it can be distinguished between human and relational capital. While the human capital covers aspects like the abilities and motivation of employees, relational capital includes especially the influence of stakeholders setting the framework for business activities. For example, customers, the regional environment, investors and business partners are part of the relational capital, which has to be sustained [2, 16].

The concept of preserving the types of capital aims to maintain capital or at least to maintain the benefit resulting from capital or similar sources of financing. The so-called "Constant Capital Rule" should guarantee that current and future generations are able to take advantage from an unchanging high life quality [19].

However, the three-dimensional view of sustainability can lead to multiple assignments and allocation issues. For example, there are discussions, if the human capital is considered to be part of the social or economic capital [13]. Considering the relations between the different forms of capital, it is questionable, if a substitution between them should be allowed to maintain a constant staff of capital [1]. In this context, it is distinguished between the strong and the weak contribution to sustainability. Strong sustainability comprises the improvement of one dimension, while maintaining or improving the other two dimensions. A weak contribution to sustainability is, for example, the improvement of one dimension, while another dimension is deteriorating and the overall ratio is improving. If the overall level is deteriorating, there is no positive contribution to sustainability [20; 21].

2.2 Sustainability management: The extended triangle of sustainability

Sustainability Management aims to establish sustainability on a microeconomic level. In the following, sustainability management comprises all systemic business activities, which support the achievement of ecological, social and economic objectives in a company [2]. This definition comprises the demands of long-term economic growth, ecological balance and social progress [22].

The extended sustainability triangle is trying to establish relations between the corners and therefore weaken the conflict of strong and weak sustainability.

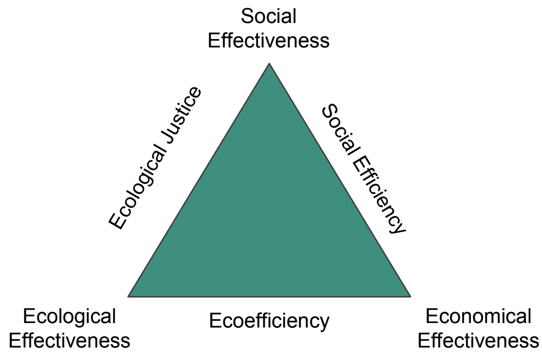


Figure 1: The extended triangle of sustainability [2; 10]

The economical effectiveness includes activities of the management, which secure the long-term existence of the enterprise and maintain its competitiveness [17]. In order to define figures for the determination of sustainability, indicators have to be selected checking the enterprise for its long-term perspective [2].

The ecological effectiveness includes corporate activities reducing the overall environmental pollution and therefore maintaining the ecological capital. In order to achieve that, input (resource consumption) and output (environmental pollution) accompanying production have to be reduced [3; 17].

Regarding the social effectiveness, enterprises are asked to increase their positive social achievements and to reduce their negative social impacts. Enterprises are socially embedded institutions, which have to consider their social interactions with individuals, stakeholders and the society as a whole to maintain acceptance.

The intersections eco-efficiency and socio-efficiency comprise corporate activities, which implement environmental protection and social engagement in a cost-effective and corporate value-adding way [3]. In order to measure those efficiency areas, indicators are used, which have influence on both dimensions (e.g. accidents at work per employee) [1].

The challenge of sustainability management is to identify the connections of ecological and social activities with economic success. In most cases the efficiency-intersections have a direct link to corporate success by reducing costs or increasing profits [2].

3 BENCHMARKING – LEARNING FROM THE BEST

This chapter serves as an introduction into the subject of Benchmarking. The first part defines the term “Benchmarking”, while the second introduces the BenchmarkIndex-Analysis provided by The Fraunhofer Institute for Production Systems and Design Technology (IPK).

3.1 Definition of benchmarking

Benchmarking as a management tool for enterprises was developed by Robert C. Camp. He defined Benchmarking as “the search for solutions, which are based on the best methods and procedures of industry, the ‚Best Practices‘, and are leading enterprises to top performances” [23]. Benchmarking is thereby a continuous process comparing products, services, processes and methods across multiple enterprises to identify success potentials [24].

3.2 The BenchmarkIndex: Indicator-based benchmarking for small and medium-sized enterprises

The BenchmarkIndex-Analysis conducts sector-specific, indicator-based benchmarking and was particularly developed for the demands of SMEs. The BenchmarkIndex supports decision makers in the determination of business objectives, in the development and the review of corporate strategies as well as in the prioritization of activities. With the use of key indicators, enterprises have the possibility to evaluate their performance comprehensively and objectively. In this way enterprises are not only able to identify their strengths and weaknesses, but also to reveal cause-effect relationships. In the course of the BenchmarkIndex-Analysis SMEs compare their indicators with other SMEs having similar prerequisites [24].

The BenchmarkIndex is based on the Balanced Scorecard (BSC) developed by Kaplan and Norton. Besides financial indicators, the method of the BSC includes also soft factors and intellectual capital to capture the enterprise’s performance holistically [2]. Kaplan’s and Norton’s approach takes the financial, custom and internal process perspective into account as well as the perspective of learning and growth [2; 25; 20].

4 ANALYSIS OF THE BENCHMARKINDEX CONCERNING SUSTAINABILITY

The objective of this procedure was to examine to what extent the indicators of the BenchmarkIndex are already sustainable. Therefore, a classification model was derived to assess the indicators from the currently existing BenchmarkIndex in a systematic way.

4.1 Sustainability-related classification model

The following classification concept is mainly derived from the ideas of Hauf and Kleine [13; 14] and is based on the sustainability triangle. The sustainability triangle alone is not able to achieve a clear classification of indicators regarding the areas of tension between the three sustainability dimensions. The intersection model puts three circles, representing each one of the dimensions, on top of each other to symbolize the possibility of multiple assignments. The pillars are therefore no separate dimensions any more, but interacting sections. The application of a classification model for the classification of indicators requires on the one hand, the junction of multiple goals, which is achieved by the intersection model. On the other hand, the maintenance of sufficient differentiation between sustainability aspects to reach a clear assignment of key indicators is necessary. As a result, Hauff and Klein combine the two models. The interpretation of this model is based on the following circumstance: The further away a field is from a corner point, the less it can be assigned to the respective dimension. Following that, there are three different groups of fields [13; 14].

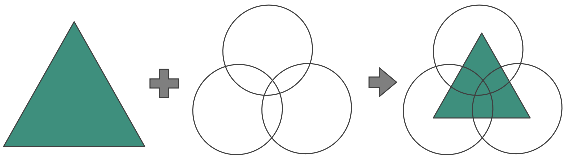


Figure 2: Advancement of triangle of sustainability [13; 14]

Indicators associated with these areas are predominantly determined by only one dimension of sustainability. Those are used to achieve absolute (effective) goals.

Indicators associated with these fields are determined by 2 dimensions of sustainability and are used to achieve relative (effective) goals.

Indicators associated with the central field are equally determined by all three dimensions of sustainability.

A mathematically rigorous interpretation of the classification model would make it possible to map the exact position of the Indicators to the three dimensions. This type of application is similar to the Gibbs's triangle method mostly applied in soil science, but far beyond the purpose of this exercise [14].

The level of detail for the present work provides a gradation, as shown in Figure 3. A "+" symbolizes that a field has a reference to the respective pillar of sustainability. An "o" symbolizes a connection of lesser importance. Based on the classification model, the indicators of the BenchmarkIndex have been examined and structured in terms of sustainability.

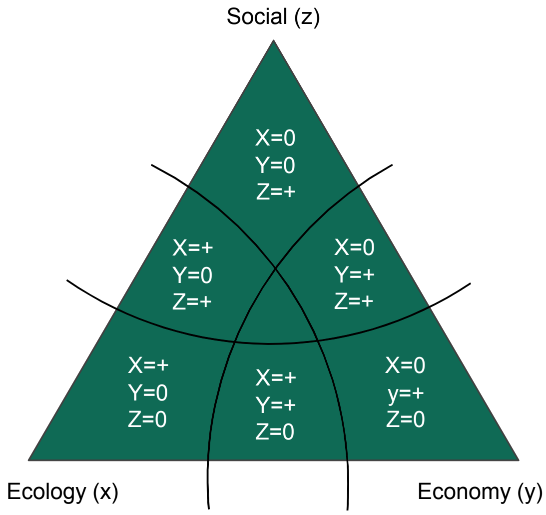


Figure 3: Classification model for sustainability analysis [14]

The procedure of classifying the existing indicators of the BenchmarkIndex is a standardized process consisting of two steps: First, the indicators have to be defined, which in most cases involve a formal description of the indicators. In a second step, the indicators are subsumed to the respective success factor, which should be measured. Using the success factor approach, it can be examined, if an assignment to one of the three sustainability dimensions is possible.

The basis of the classification forms has already presented in the capital stock theory above. Hereby, it is especially important to test, if the indicator and therefore the respective success factor contribute to the maintenance or increase of those types of capital.

If an indicator contributes to the maintenance or the increase of the human or relational capital, it can be allocated to the social sector. In this case, a one-dimensional effect is given, if the indicator has no (direct) impact on the economic value orientation of the company. For example, the number of accidents in a company is a social success factor that also has an impact on the economic dimension, since downtime and insurance costs may be impaired. A similar procedure is performed for the ecological classification.

Regarding the economic dimension, in particular the principle of long-term orientation is essential. Based on the definition of the Balanced Scorecard (BSC) all indicators have an economic relevance and a monitoring function. Accordingly, an economic indicator that can be qualified as sustainable must be able to monitor the long-term competitiveness and livelihood of a company.

4.2 BenchmarkIndex: Current level of sustainability

As a result of the analysis, the BenchmarkIndex contains a total of 22 indicators that have a reference to sustainability, which is equivalent to one third of all indicators. From an overall perspective, the BenchmarkIndex can be considered as partly sustainable. However, a more detailed analysis revealed that more than half of the sustainable indicators (13 indicators) evaluate only the economical way of doing sustainable business.

Figure 4 below shows the indicators of the BenchmarkIndex that already include sustainable aspects and the respective areas of sustainability within the classification model they have been allocated to. The result highlights that even if the BenchmarkIndex already includes a number of sustainable indicators, there is still a huge potential for improvement in the areas of eco- and socio-effectiveness as well as their intersections.

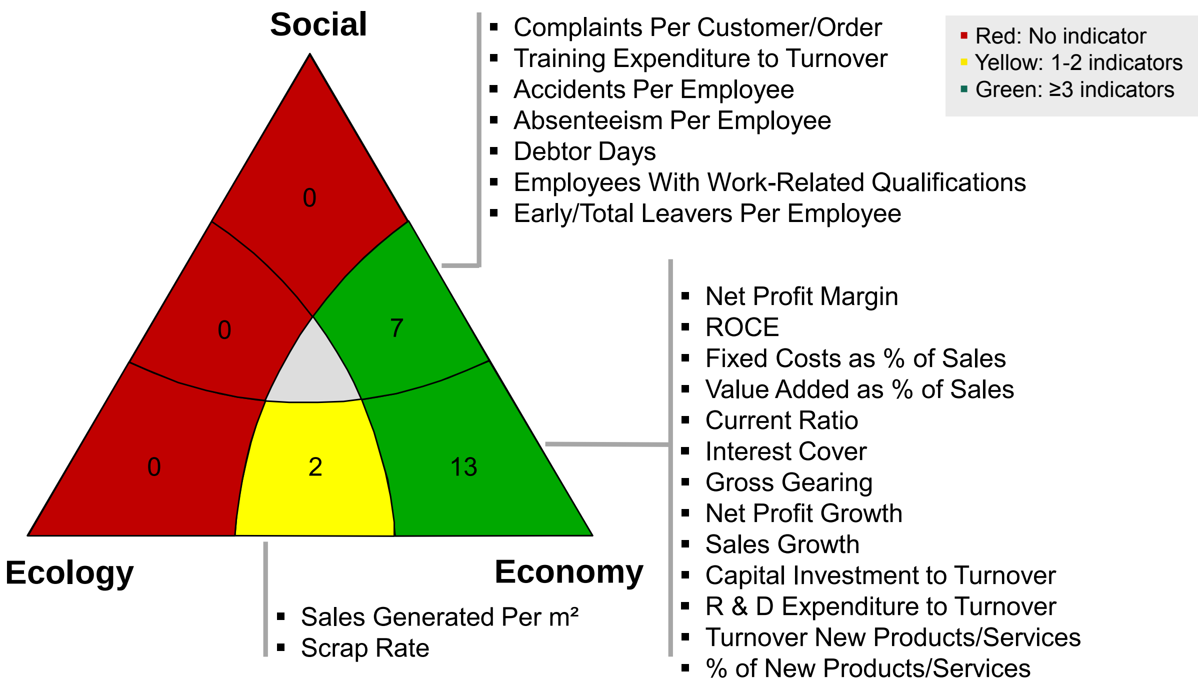


Figure 4: BenchmarkIndex - Current level of sustainability by dimensions

4.3 Selection process of indicators for a highly sustainable BenchmarkIndex

The first step for a reasonable restructuring of the BenchmarkIndex includes the identification of potential indicators that are suitable for cross-company-comparisons. This suggests that these specific indicators need to have a high level of abstraction and are of central importance for a variety of companies.

The second step provides a reasonable structuring of the identified indicators by clustering them. Thus, it can be determined, which aspects of sustainability in the ecological and social perspectives, are not covered by the BenchmarkIndex yet.

For the third step, the selection of indicators has to meet three main criteria in order to be considered:

- Transparent and comprehensible approach in order to guarantee the highest possible objectivity.

- Selection in accordance to the existing indicators of the BenchmarkIndex considering the full range of sustainability perspectives.
- Specific requirements for SMEs: Efforts and cost to capture and handle new indicators as low as possible.

To comply with these requirements a wide spectrum of data sources has been consulted including perspectives of scientific institutes, practice-oriented associations, financial analysts, as well as norms and legislations. Data sources that were used are [26; 27; 28; 29; 30; 31; 32; 33]:

- Global Reporting Initiative (GRI)
- Future Ranking of the Institute for Ecological Economy Research (IÖW)
- Introduction of Sustainable Management in Small and Medium-sized Enterprises by the Association of German Engineers (VDI 4070)
- Sustainable Excellence Approach (Susex)
- Environmental Management Systems: DIN 14000 and EMAS (Eco-Management and Audit Scheme)
- Cross-sectorial indicators of the European Federation of Financial Analysts Societies (EFFAS)
- s8000 standard of the Association Social Accountability International (SAI)
- German Sustainability Code developed by the Council for Sustainable development

Selection and structuring of social indicators

Besides the general requirements mentioned above, the selection of social indicators was performed based on the stakeholder approach regarding the requirements of

- Employees in term of employment and satisfaction, safety and health, education and education, diversity and equality
- Customers in terms of consumer protection, product lifecycle management (customer-friendly use and disposal)
- Business partners in terms of fair competition, human rights unscrupulous procurement practices and reliability in legal provision
- Society in term of transparency, social commitment, environmental protection, compliance with the legislation

For the structuring of social indicators, it was necessary to assign these not only to stakeholders, but also to subordinate request of a stakeholder group.

Selection and structuring of ecological indicators

The selection and the structuring of ecological indicators have been carried out using an input/output balance. Thereby, a systematic inclusion of all relevant material and energy flows of incoming and outgoing environmental parameters within the production processes becomes possible [34]. On the input side of the balance mainly natural raw materials, consumables and the total energy consumption play an important role for the production of products. On the output side, the environmental impact of the product itself becomes significant, for example in terms of practical use and disposal [34; 35].

The result matrixes for both evaluations are shown in Figure 5. The vertical axis prioritizes in both cases the citations in the before mentioned literature/data sources. Regarding the social perspective, the horizontal axis in the left diagram indicates if an indicator addresses a request of an already considered or new stakeholder group. Since seven social indicators are already included in the BenchmarkIndex the search for new indicators focuses on those which provide the greatest benefit for additional stakeholder groups. On the horizontal axis in the right diagram, the practicability in terms of capturing and handling ecological indicators is evaluated. In both cases, the best results are located in the upper right quadrant.

As already emphasized, within the equilateral triangle of sustainability, each dimension is considered to be equivalent. Since the approach of this work also intended to cover the topic sustainability in a holistic way, it is logical to select and distribute the identified indicators to the fields of the classification model evenly. This requires also the observation of the socio-ecological intersection area, which is not covered by the identified indicators so far. Hereby, the involvement of key stakeholders such as employees, suppliers and public relations in activities of environmental protection and communication plays an important role [34]. Thus in a similar approach, the indicators "number of trained staff in environmental protection", "suppliers with environmental management systems" and "number of positive ecological media resonance" have been identified and added to the socio-ecological dimension of the sustainability triangle.

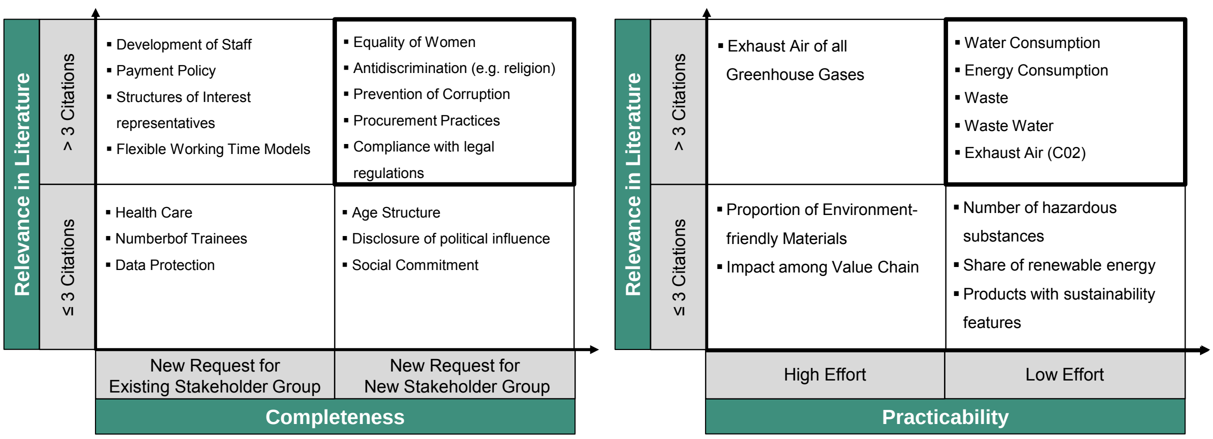


Figure 5: Result matrix prioritizing social (left) and ecological (right) sustainability indicators

4.4 Result of the Selection Process

In analogy to Chapter 4.2, Figure 6 summarizes the prioritized indicators for all sustainability dimensions and integrates them in the classification model for the analysis of the BenchmarkIndex.

All new indicators are marked in bold, while the remaining ones were already included in the BenchmarkIndex before. In order to achieve a holistic coverage of all aspects of sustainability it was necessary to add 12 new indicators to the already existing 22 of the BenchmarkIndex. The minimum number of 3 indicators per fields was derived from a survey of investors and analysts of DAX-listed companies in 2009. As a conclusion, the survey recommended to use at least 15% non-financial performance indicators from the environmental and social perspective to get sustainable and meaningful results at the end [36].

This measure increased the measurability of sustainability aspects within the BenchmarkIndex by more than 50%. Even compared to the whole range of 66 indicators included in the BenchmarkIndex, this improvement still amounts for 18%. As a consequence, all areas of sustainability are equally represented by the enhanced BenchmarkIndex today. This enhancement was achieved by conducting a thorough gap analysis prior to the selection of indicators. This analysis formed the basis for an expedient complementation, since it served to identify and describe the existing measurement gaps and allowed to derive specifications for the necessary complementing indicators. In this context, the BenchmarkIndex-Analysis can equally add a significant contribution to the sustainability efforts of SMEs in the world.

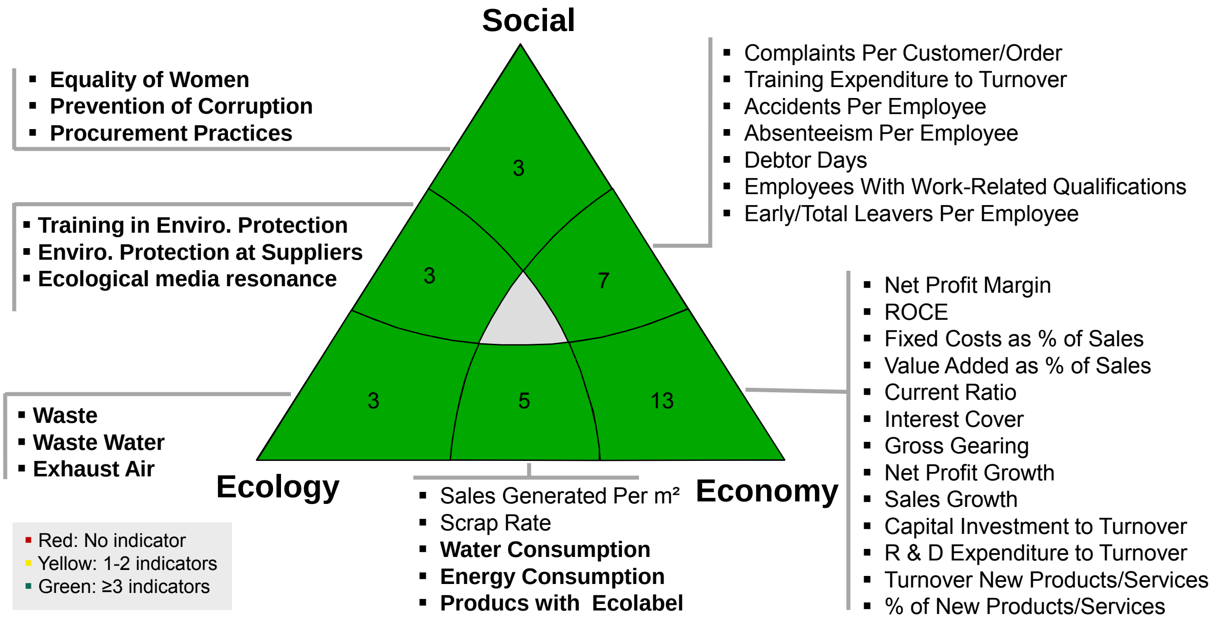


Figure 6: BenchmarkIndex - Improved level of sustainability by dimensions

5 SUMMARY

The BenchmarkIndex is a management instrument that allows companies to comprehensively evaluate their business performance based on selected indicators of the Balanced Scorecard. Due to the increasing scarcity of resources and the corresponding importance of sustainability management within today's business environment, a critical gap analysis of the current capabilities of the BenchmarkIndex has been carried out. As a consequence, improvement potentials particularly in the fields of social and environmental sustainability have been identified. In this context, suitable indicators were systematically evaluated and selected to complement the BenchmarkIndex according to the new requirements reflected in the market environment. Thereby, the sustainability orientation of the BenchmarkIndex could be increased by more than 50%. Based on the supplementary sustainability indicators, it can be stated that the BenchmarkIndex holistically covers all aspects of sustainability management today, far beyond the economic perspective.

6 ACKNOWLEDGEMENT

The results are part of the ongoing research project “Sustainable Manufacturing – Shaping global Value Creation”. The project is funded by the German Research Foundation DFG.

7 REFERENCES

[1] Müller, F.; Liesen, A.; Marwede, M.; Handke, V.; Hahn, T.; Figge, F.: Der Sustainable-Value-Ansatz in kleinen und mittleren Unternehmen, Berlin, 2009.

[2] Schaltegger, S.; Dyllick, T. (Hrsg.): Nachhaltig managen mit der Balanced Scorecard, Gabler-Verlag, Wiesbaden, 2002.

[3] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) (Hrsg.): Nachhaltigkeitsmanagement in Unternehmen: Von der Idee zur Praxis, Berlin, 2007.

[4] Linne, G.; Schwarz, M. (Hrsg.): Handbuch Nachhaltige Entwicklung – Wie ist nachhaltiges Wirtschaften machbar?, VS Verlag, 2003.

[5] Baetge, J.; Deloitte (Hrsg.): Best Practices bei SD-KPIs, Beispiele guter Berichterstattung zu Sustainable Developement, Key Performance Indikators in Lageberichten, 2006.

[6] Statistisches Bundesamt (Hrsg.): Statistisches Jahrbuch 2007, Wiesbaden,2007.

[7] Kohl, H.: Integriertes Benchmarking für kleine und mittlere Unternehmen, Fraunhofer IRB Verlag, Berlin, 2007.

[8] Bundesministerium für Wirtschaft und Technologie (BMWi): Mittelstand: Leistung durch Vielfalt, Berlin, 2009.

[9] United Nations (Hrsg.): Report of the World Commission on Environment and Development (WCED): Our Common Future, 1987.

[10] Hauff von, M.; Kleine, A.: Nachhaltige Entwicklung: Grundlagen und Umsetzung, Oldenbourg Verlag, München, 2009.

[11] Corsten, H.; Roth, S. (Hrsg.): Nachhaltigkeit: Unternehmerisches Handeln in globaler Verantwortung, Gabler Verlag, Wiesbaden, 2012.

[12] Elkington, J.: The Sustainability Advantage: Seven Business Case Benefits of a Triple Bottom Line, 2002.

[13] Kleine, A.: Operationalisierung einer Nachhaltigkeitsstrategie: Ökologie, Ökonomie und Soziales integrieren, Gabler Verlag, Wiesbaden, 2009.

[14] Hauff, M.; Kleine, A.: Methodischer Ansatz zur Systematisierung von Handlungsfeldern und Indikatoren einer Nachhaltigkeitsstrategie, 2005.

[15] Hediger, W.: Sustainable Development and Social Welfare; in: Ecological Economics, 2000.

[16] Mertins, K.; Seidel, H. (Hrsg.): Wissensmanagement im Mittelstand: Grundlagen – Lösungen – Praxisbsp., Springer Verlag, Berlin, 2009.

[17] Wilkens, S.; Effizientes Nachhaltigkeitsmanagement, Deutscher Universitätsverlag, 2007.

[18] Küker, S.: Kooperation und Nachhaltigkeit: Ein prozessorientierter Gestaltungsansatz für eine Analyse der Beiträge von Kooperationen zum nachhaltigen Wirtschaften, Verlag Dr. Kovac, 2003.

[19] Figge, F.; Hahn, T.: Sustainable Value Added - Ein neues Maß des Nachhaltigkeitsbeitrags von Unternehmen am Beispiel der Henkel KGaA, Zeitschrift Wirtschaftsforschung, Ausgabe 73, 2004.

[20] Figge, F.; Hahn, T.; Schaltegger, S.; Wagner, M.: Sustainability Balanced Scorecard: Wertorientiertes Nachhaltigkeitsmanagement mit der Balanced Scorecard, 2001.

[21] Deegen, T.: Ansatzpunkte zur Integration von Umweltaspekten in die Balanced Scorecard, 2001.

[22] Eckelmann, O.: Strategisches Nachhaltigkeitsmanagement in der pharmazeutischen Industrie, Deutscher Universitätsverlag, 2006.

[23] Camp, R. C.: Benchmarking, Hanser Fachbuchverlag, 1994.

[24] Mertins, K. ; Kohl, H.: Benchmarking – Leitfaden für den Vergleich mit den Besten, Symposion Publishing Verlag, Düsseldorf, 2009.

[25] Kaplan, R.; Norton, D.: The Balanced Scorecard: Strategien erfolgreich umsetzen, Stuttgart, 1997.

[26] Verein Deutscher Ingenieure (VDI) (Hrsg.), Richtlinie 4070: Nachhaltiges Wirtschaften in kleinen und mittelständischen Unternehmen, 2006.

[27] Institut für ökologische Wirtschaftsforschung (IÖW) Future e.V. (Hrsg.) http://www.ranking-nachhaltigkeitsberichte.de, 2013.

[28] Beys, K. (Hrsg.): Lexikon der Nachhaltigkeit, Aachener Stiftung, http://www.nachhaltigkeit.info, 2013.

[29] European Federation of Financial Analysts Societies (EFFAS), http://effas.net, 2013.

[30] Global Reporting Initiative (GRI), www.globalreporting.org, 2013.

[31] Rat für Nachhaltige Entwicklung (Hrsg.), Der Deutsche Nachhaltigkeitskodex(DNK), Texte Nr. 41, 2012.

[32] Social Accountability International, www.sa-intl.org, 2013.

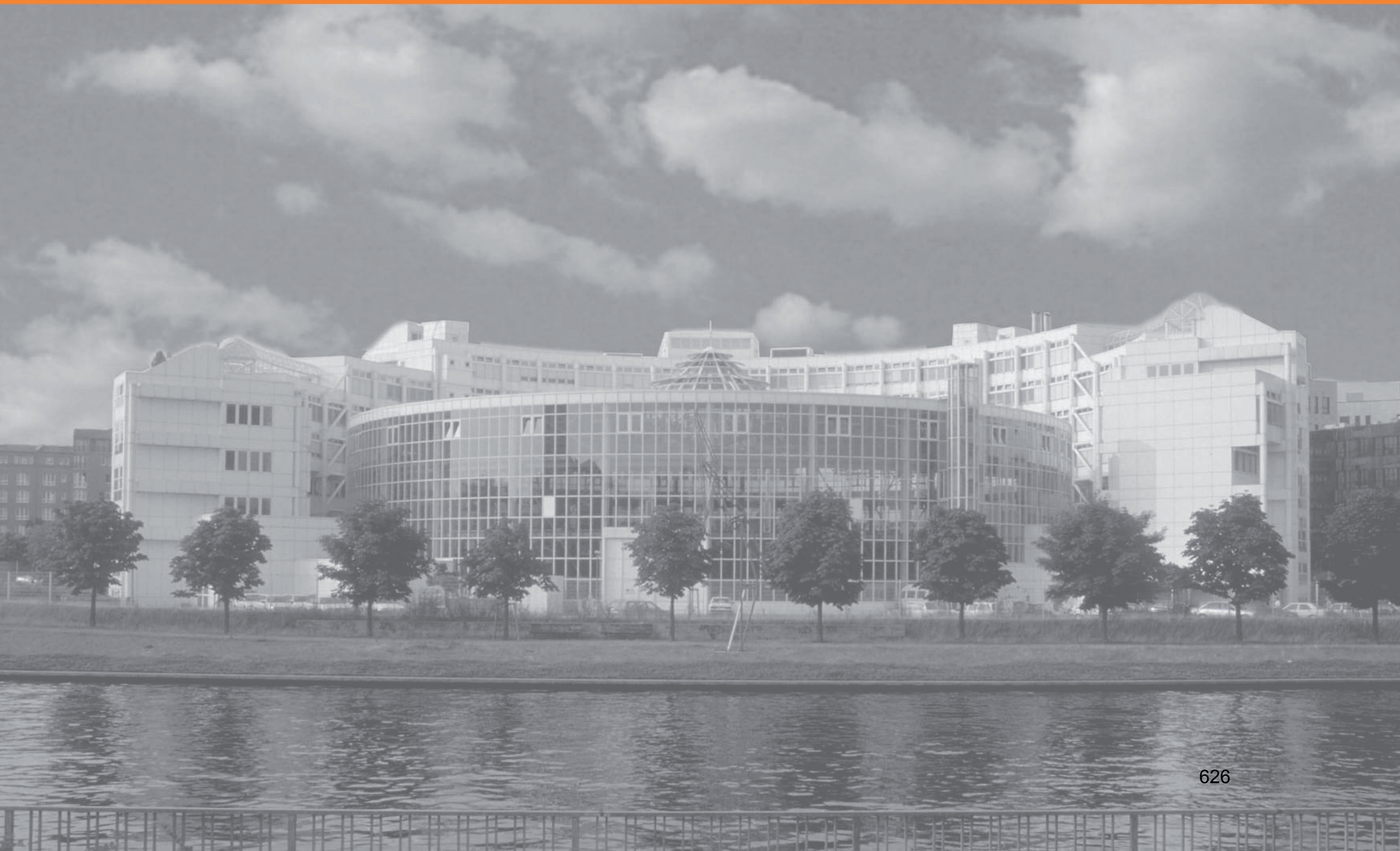
[33] Eco-Management and Audit Scheme (EMAS), http://www.emas.de, 2013.

[34] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) (Hrsg.): Umweltcontrolling, Vahlen Verlag, München, 2001.

[35] Jasch, C.: Was ist und kann eine Ökobilanz?: Ökobilanz, Umweltcontrolling und Environmental Auditing, in: Schriftenreihe 8/1992 des IÖW, 1992.

[36] Hesse, A.: SD-KPI Standard 2010 – 2014: Mindestberichtsanforderung für bedeutende Nachhaltigkeitsinformationen, 2010.

Session 18
Tools and Technologies



GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

18.1 Investigation of the upgrading potentials of out-of-date cutting machine tools to promote sustainable and global value creation

E. Uhlmann [1], K. Kianinejad [1]

[1] Department for Machine Tools and Factory Management, Technical University Berlin, Germany

Abstract

Cutting machine tools play a major role in global value creation. During last decades machine tools have been developed regarding production efficiency, working accuracy and flexibility. Nevertheless there exist a large number of conventional milling machines particularly in developing countries, which cannot be applied effectively in global creation networks due to the low processing efficiency and low flexibility. Upgrading existing machines can save raw material and energy resources and supports sustainability. In this paper the improvement potentials of out-of-date machine tools without exchanging system relevant components have been investigated and necessary tests and measurements have been implemented. Two machine tools, a newer and an older milling machine as representative example were compared and some possible improvement solutions of the older machine have been proposed concerning working accuracy and flexibility.

Keywords:
Machine tool, Optimization, Working accuracy, Performance comparison, Sustainability

1 INTRODUCTION

1.1 Present Situation

The global production of machine tools has almost tripled in last two decades. In 2011 the production of machine tools has increased by 30% compared with 2010 and exceeds significantly previous record of 54.3 billion Euros in 2008 [1]. With 73% share of total global production volume in 2011 in Germany, cutting machine tools have a leading position among other machine tools [1]. Ascending production of machine tool can be an indicator of rapidly growing demand for machine tools in near future. To meet these demands, by means of production of new machine merely, huge amount of material and energy resources are required. At the same time there already exist a remarkable number of machine tools which still can be considered as useable. According to a VDMA report the average lifetime of NC-controlled metal working machine tools estimated by manufacturers is about 9.5 year [2]. Despite of estimated lifetime, a survey of the German machine tool builders' association [3] shows that about only 43% of used machine tools has maximum life span of 25 year or more. According to the survey over 80% of the machine tools are retrofitted or refurbished between 5 years and 15 years. Change of guidance and bearings, change of core components and overhaul are the most dominating measures of retrofitting and refurbishment [3]. The above mentioned statistics clarifies that a large proportion of machine tools are not going to be used longer than 25 years and will be replaced at the end of life span. The main idea in this paper is to investigate the improvement potentials of out-of-date machine tools without retrofitting or refurbishing. This approach can on one hand extend the lifetime of machine tools. On the other hand this approach can be seen as an alternative method to retrofitting and refurbishment. These two aspects highly support the sustainability since a partial or complete renewal of machine tools or machine tool parts can be prevented. In order to be able to study the improvement potentials of out-of-date machines, it should be understood why these machines are outdated. To answer this question it should be clear, which developing trends the machine tools have experienced within last 3 decades.

1.2 Developing Trends

Considering current topics in research and development communities and recent publications on technological trends of machine tools four main fields of developing can be identified [4] and [5]:

- High-speed and high-efficiency machine tools
- Multifunctional and flexible machine tools
- High-Precision and Ultra-Precision machine tools
- Advanced and Intelligent controlled machine tools

These trends can also be seen as an indicator of demands and needs on present and future production processes. The machine tools should be able to meet high requirements concerning efficiency, working accuracy, flexibility and control systems. The machine tools which cannot meet some or all of above requirements are considered as outdated. In order to find a quantified measure for increased requirements two machine tools, an outdated machine and a new machine, are compared. In this way the weak spots of outdated machine under operational conditions could be identified. Beside sustainability the economic aspects of outdated machine tools are becoming increasingly important. Second-hand machinery and equipment to the value of more than 75 billion Euros are traded yearly, mostly to developing countries and emerging markets [6]. Almost unnoticed the transfer of second-hand machinery and equipment has now become an important business sector. Second-hand machinery and equipment from industrialized countries are recognized by enterprises in

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

developing countries as a low-cost and fast solution to the problem of replacing outdated machinery and/or building up new capacities [6]. Upgrading outdated machine tools will enable enterprises in developing countries to manufacture products with higher quality und lower costs, so that new capacities for participation in global value creation can be created.

2 APPROACH

Based on the comparison of two milling machine tools, weak points of the outdated machine tool were identified at first. The compared machine tools are frequently in use, so that quantitative measures for weak points of outdated machine under operating conditions could be identified. At the second step, based on determined weak points, sustainable improvement solutions of outdated machines could have been proposed, which can be realized in context of sustainability. This means an upgrading of machine tools without changing core components like feed drives and spindle unit. Furthermore, the possible solutions have been considered to be generally applicable to other comparable milling machine types.

Milling process play an important role among other manufacturing processes. Milling machine tools and machining centers made up of 30% of German machine tool production in 2011 [7]. At the same time the metal working machine tools experience a continuous shift from non-CNC machine tools to CNC-machine tools [8]. Therefore the results of comparison between CNC milling machines can affect a large number of exciting milling machine tools.

The older machine tool, FP4NC, DECKEL GmbH, Germany, is a vertical knee-type CNC milling machine with 4 simultaneously controlled axis built in year 1986 (Figure 1).

Figure 1. FP4 milling machine, DECKEL GmbH.

The newer machine tool, DMU-50, DECKEL MAHO GmbH, Germany is a vertical universal 3+2 axis CNC milling machine manufactured in year 2008 (Figure 2).

Figure 2. DMU-50 universal milling machine, DECKEL MAHO GmbH

Both compared machine tools have common working space for stand-alone solutions of between 450 mm and 560 mm per linear axis and are suitable for machining of single parts and small series. Concerning age (27 years) and technology, the FP4 milling machine has been considered as a representative example for an outdated machine tool. Further technical information available for these machine tools including main drive, feed drives, working space, control system, power of main drive and maximum velocity of feed drives are shown in Table 1.

Machine type	CNC Milling Machine	CNC Universal Milling Machine
Manufacturing year	1986	2008
Manufacturer	Deckel GmbH, Germany	Deckel Maho Seebach GmbH, Germany
Designation	FP4NC	DMU 50
Base area [m]	2 x 1.6	1.2 x 1.4
Number of machine axes	4	3 + 2
CNC control system	Grundig/Dialog 4	Heidenhain/ ITNC 530
Travels X/ Y/ Z [mm]	560/ 500/ 450	500/ 450/ 400
Feed speed X/ Y/ Z [mm/min]	Up to 3600	Up to 24000
Maximum spindle power [kW]	4.0	13.0
Spindle revolution [1/min]	Up to 3150	Up to 10.000
Tool holder system	SK 40	SK 40

Table 1. Technical information of compared milling machines.

The comparisons are carried out in following main fields: working accuracy, dynamic behavior and productivity. The above fields represent some of the important developing trends by machine tools and are more relevant for standalone milling machines

3 EXPERIMENTAL AND ANALYTICAL PROCEDURE

At the first step, aspects of the geometrical, kinematic and dynamic behavior of the machine tools have been studied. It is important to notice that a comprehensive comparison in each of above fields is extremely time consuming, so that some representative and more significant aspects are focused. To find a measure for geometric behavior positioning accuracy and straightness of two machines tools are measured along all linear axes using laser interferometer. Due to high precision and high measuring repeatability laser interferometer is particularly adequate for above measurements. Furthermore, it is possible to carry out the positioning and straightness tests dynamically by means of laser interferometry which aims at the analysis of machine tool kinematics.

To analyze dynamic behavior, the dynamic characteristic of the machine structure and cutting tool is deduced at first from measured frequency-response functions at the tool center point (TCP). To measure frequency-response of TCP, the structure is excited at the TCP in x- and y-direction of the machine tool coordinate system using an impact hammer type Kistler 9722A500 with a mass of m = 0.2 kg. The impact hammer is equipped with a steel tip. The response in x- and y-direction of the machine tool coordinate system is measured at the TCP with use of a triaxial acceleration sensor type Kistler 8692C10M1. The used bandwidth is 4000 Hz. It is important to notice that the described measurements have been carried out under in idle state. A comprehensive modal analysis of FP4 machine has been carried out by [9].

Finally, based on analytical equation of Kienzle, the theoretical accessible removal rate of both machine tools has been estimated for several milling strategies. In this way the milling process efficiency of both machines can be compared. However, due to stability of milling process, the estimated removal rate should be considered merely as a measure of real accessible removal rate under machining conditions. Furthermore, the results may vary for different cutting materials and different conditions of cutting tools. The following calculations are applied for estimation of mechanical power of milling processes resulting from cutting force. To calculate the cutting force, the cutting velocity (v_c) has to be determined at first (equation (1)).

$$v_c = \frac{D \cdot \pi \cdot n}{1000} \tag{1}$$

In equation (1) D represents tool diameter and n spindle speed in revelations per min. To calculate cutting forces, equation of Kienzle is used. Therefore, the value for specific cutting forces (k_c) is needed. k_c can be calculated using equations:

$$k_c = \frac{k_{c1}}{{h_m}^m} \tag{2}$$

and

$$h_m = \frac{114.6}{\varphi_s} \cdot f_z \cdot sin\,\kappa \frac{a_e}{D} \tag{3}$$

In equation (2) and (3) k_{c1} represent principal value of specific cutting force [N/mm²], a_e contact width [°], κ contact angle, φ_s cutting arc angle [°], f_z feed per tooth [mm], m slope and h_m average chip thickness [mm]. With k_c it is possible to estimate the average force in milling process (F_{cmz}) and calculate the mechanical power which is needed for milling (P_c):

$$\frac{F_{cmz}}{a_p} = \frac{1}{sin\,\kappa} \cdot h_m \cdot k_c \cdot k_\gamma \cdot k_V . k_{ver} \tag{4}$$

$$\frac{P_c}{a_p} = \frac{F_{cmz} \cdot v_c \cdot z_{iu}}{60000} \tag{5}$$

In equations (4) and (5) is a_p the cutting depth. k_γ, k_V and k_{ver} represent correction factors for processing material, tools material and tool conditions and z_{iu} stand for number of tooth in use. By taking the efficiency of spindle motor η into account, an approximation of the needed spindle power (P_A) can be evaluated:

$$P_A = \frac{P_c}{\eta} \tag{6}$$

Considering above assumption the removal rate of milling machines has been calculated using accessible spindle power, maximum feed velocity of linear axis and maximum revolution of spindle.

4 RESULTS

4.1 Working accuracy

Figure 3 and Figure 4 illustrates the positioning accuracy along x- and y-axis of each machine's coordinate system. Table 2 and Table 3 clarify a static analysis of measured deviations according to ISO 230-2. The travel distance of each axis is divided into 11 measuring points. The measurements are carried out at measuring points using pilgering step method with 3 and 5 steps.

	DP4	DMU-50
Mean backlash [µm]	1.2	0.8
Mean deviation [µm]	57	26
Repeatability [µm]	17	2
Accuracy [µm]	62	29

Table 2. Static analysis of measured deviations of positioning according to ISO 230-2 along x-axis.

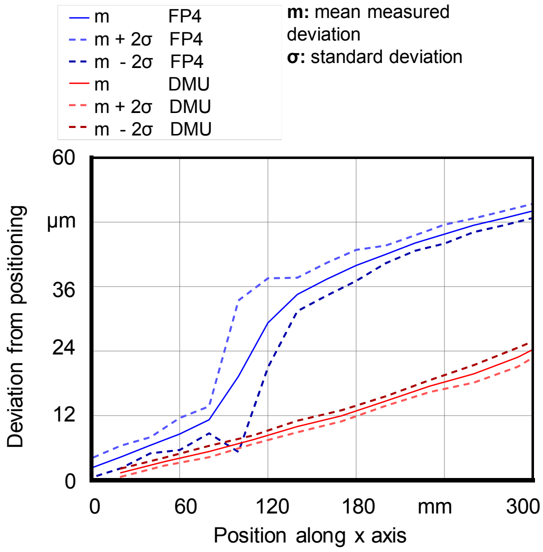


Figure 3. Deviation from positioning along x-axis

Figure 3 and Table 2 point out that the positioning accuracy of FP4 machine is significantly lower than DMU-50 machine along x-axis. The magnitude of positioning accuracy along y-axis for both machines is comparable (Figure 4).

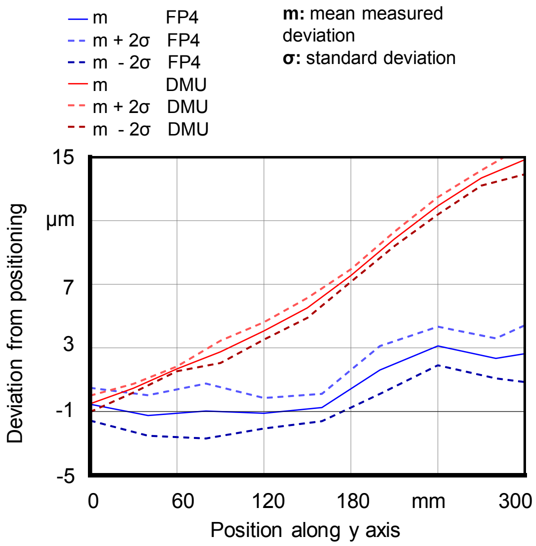


Figure 4. Deviation from positioning along y-axis

However, Table 2 and Table 3 show that DMU-50 machine is significantly more accurate concerning backlash and repeatability of measured results for both x- and y-axis. The inaccuracy of FP4 machine can be a result of defects in guides and feed drive system or inaccuracy of CNC system. It can also be seen that the deviation of both machines has diverse characteristics and properly have different origins.

	DP4	DMU-50
Mean backlash [µm]	1.0	0.3
Mean deviation [µm]	6	15
Repeatability [µm]	3	1.5
Accuracy [µm]	9	16

Table 3. Static analysis of measured deviations of positioning according to ISO 230-2 along y-axis.

Furthermore the straightness accuracy of FP4 machine is measured along x- and y- axis of machine coordinate system and in x-y and x-z coordinate plains (Table 4). In this way, it could be concluded that the guides of FP4 machine cannot be responsible for inaccuracy along x-axis.

	x-z-plain	x-y-plain
Bidirectional accuracy [µm]	13.1	16.6
Bidirectional repeatability [µm]	13.1	15.0
Mean backlash [µm]	0.3	0.7
Mean deviation [µm]	5	5

Table 4. Static analysis of measured deviations of straightness according to BS 3800 along x-axis for FP4 milling machine.

Figure 5 illustrates the comparison of compliance-frequency G response of both machines in direction of x- and y- axis of machines coordinate system.

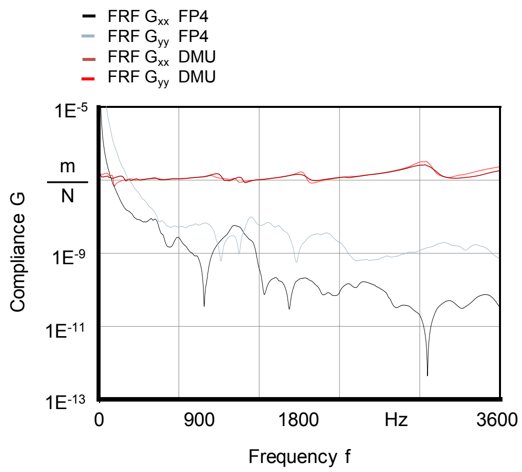


Figure 5. Comparison of frequency response function in x- and y-direction .

Figure 5 clarifies that the DP4 milling machine tool has considerable higher stiffness comparing to DMU-50 machine. The reason for this is an oversizing of dp4 machine by construction. The DMU-50 machine is constructed based on light lightweight design and efficiency.

4.2 Productivity

The theoretical removal rate for different processing parameter has been compared using equations (1) to (6). For each processing strategy the combination of processing parameters have been chosen in such a way that a maximum power of spindle can be utilized for respective strategy. The comparison has been carried out for two materials: steel 1.0038 and aluminum alloy 2017A.

Table 5 and Table 6 show the comparison of different processing strategies for aluminum alloy.

	Str. 1	Str. 2	Str. 3	Str. 4
Revolutions of main spindle [Rev/min]	2200	3150	3150	3150
Cutting velocity [m/min]	138	197	197	197
Feed velocity [mm/min]	200	300	3600	3600
Cutting width [mm]	18	12	1	2
Feed per tooth [mm]	0.023	0.024	0.29	0.29
Average cutting force [N]	95	43	124	161
Mechanical power of cutting [kW]	0.16	0.16	0.12	0.22
Required power of spindle per Cutting depth [kW/mm]	0.2	0.2	0.15	0.27
Cutting depth [mm]	20	20	26.6	14.8
Required power of spindle [kW]	**4**	**4**	**4**	**4**
Removal rate [mm^3/min]	72,000	72,000	95,760	106,500

Table 5. Comparison of influence for different milling strategies for milling machine FP4, cutting tools width of 20 mm and processing material aluminum alloy 2017A.

As expected, the accessible theoretical removal rate by DMU-50 machine is significantly higher than FP4 machine. Furthermore it can be seen that a higher removal rate can be achieved for both machines by using greater feed per tooth. The results for processing of steel have shown similar tendencies and have not been discussed here. A more detailed consideration of processing parameters in Table 5 and Table 6 shows that the main restrictive factor, concerning removal rate, is maximum spindle power. Beside this, the maximum feed velocity is important.

	Str. 1	Str. 2	Str. 3	Str. 4
Revolutions of main spindle [Rev/min]	10,000	10,000	10,000	10,000
Cutting velocity [m/min]	628	628	628	628
Feed velocity [mm/min]	24,000	24,000	24,000	2,400
cutting width [mm]	3.62	1	0.76	12
Feed per Tooth [mm]	0.6	0.6	0.6	0.06
Average cutting force [N]	354.62	220.12	198.36	88.31
Mechanical power of cutting [kW]	2.08	0.66	0.52	1.04
Required power of spindle per Cutting depth [kW/mm]	2.6	0.83	0.65	1.3
Cutting depth [mm]	5	15.67	20	10
Required power of spindle [kW]	**13**	**13**	**13**	**13**
Removal rate [mm^3/min]	434,400	376,080	364,800	288,000

Table 6. Comparison of influence for different milling strategies for milling machine DMU-50, cutting tools width of 20 mm and processing material aluminum alloy 2017A.

5 SUMMARY AND OUTLOOK

Considering the above results the outdated machine exhibits at least in two fields considerable improvement potentials: increasing of working accuracy and increasing of processing efficiency.

In case of working accuracy deviations from set points can be divided into repeatable and stochastic parts. In this context by repeatable is meant a spatial and temporal reproducibility of measured deviation. One possible solution for improvement of working accuracy is to compensate the repeatable part of deviations by means of modification of program in CNC system. The repeatable deviations can be determined by systemic measuring of machine tools. Due to spatial nonlinearity of deviation and low repeatability accuracy, a compensation CNC system may not be appropriate for investigated outdated machine.

Stochastic deviation cannot be reproduced under the same initial and boundary conditions. In this context the stochastic errors can be caused by geometric, kinematic and dynamic effects. The stochastic accuracy deviations can be compensated by means of add-on mechatronic components, as an example. These components can be installed additionally on the tool center point or on machine table. By using appropriate actuators and sensors the relative position of tool and work piece can be determined and controlled. In this way a share of deviations can be compensated.

An implementation of above approaches can increase static and kinematic accuracy of an outdated machine tool with a minimal modification of machine. On one hand, this can extend the lifespan of outdated machine and prevent a complete replacement of machine tool. On the other hand, the part of inaccuracy resulting from worn or partially defect components can be compensated so that replacing or repairing of such components is not necessary. In this way material and energy resources, which are required for manufacturing and transporting of new machine or spare parts, can be saved. Concerning the enormous growing demands for machine tools on one side and scarcity of resources on the other side the above approach can facilitate the suitable value creation in global context.

From other point of view, the machine tools which are updated with above method are able to manufacture parts with higher quality or more complexity with minimal investments. This affects the efficiency and lifespan of the final product positively and has a secondary supporting effect on suitability.

In case of productivity add-on mechanical components like an external gear system can be used to increase maximum revolution of main spindle or maximum feed velocity. However due to restricted power of spindle or feed drives no significant improvement of removal rate by roughing can be achieved. This has been presented by means of above calculations. Instead an improvement of processing efficiency may be achieved by reducing of secondary processing time.

In order to determine the improvement potential of outdated machine tools comprehensively, more detailed analysis and measurements should be carried out. Particularly the machine behavior has to be studied under load and machinery conditions.

6 ACKNOWLEDGMENTS

This work was funded by the German Research Foundation (Deutsche Forschungsgemeinschaft), within the Collaborative Research Centre 1026 (SFB).

7 REFERENCES

[1] G.M.T.B. Association, The German Machine Tool Industry, Frankfurt am Main, 2011.

[2] VDMA-Kennzahlen Fertigung und Montage, 2006.

[3] V. D. Werkzeugmaschinenfabriken, Art und Umfang von Retrofit-/Refurbishing-Maßnahmen (R/R) an Werkzeugmaschinen, survey., February 2010.

[4] T. Moriwaki, Multi-functional machine tool, *CIRP Annals - Manufacturing Technology,* 2008.

[5] T. MORIWAKI, Trends in Recent Machine Tool Technologies, NTN TECHNICAL REVIEW, 2006.

[6] J. Janischweski, "The Export of Second-Hand Goods and the Transfer of Tec hnology," Berlin, 2003.

[7] G.M.T.B. Association, The German Machine Tool Industry, Frankfurt am Main, 2012.

[8] Machine tools and related machinery, Fraunhofer IZM/IPK, Berlin, 2012.

[9] E. Uhlmann, J. Mewis, P. Rasper, Microsystem and Adaptronic Machine Tool Concepts for Global Value Creation, *The 10th Global Conference on Sustainable Manufacturing,* 2012.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

18.2 Microsystem enhanced machine tool structures to support sustainable production in value creation networks

Bernd Peukert[1], Jan Mewis[1], Mihir Saoji[1], Eckart Uhlmann[1]
Stephan Benecke[2], Rolf Thomasius[2], Nils F. Nissen[3], Klaus-Dieter Lang[2,3]
1 Institute for Machine Tools and Factory Management, Technische Universität Berlin, Germany
2 Research Centre for Microperipheric Technologies, Technische Universität Berlin, Germany
3 Fraunhofer Institute for Reliability and Microintegration, Berlin, Germany

Abstract
The modularization of machine tool frames is a promising approach to support sustainable manufacturing in global value creation networks. The idea of designing single versatile lightweight and accuracy optimized (LEG²O) modules allows for innovative concepts with respect to mobility, configurability and adaptability. This contribution focuses on possible use-case scenarios that involve modular machine tool frames equipped with microsystems providing enabling functionalities, e.g. self-identification and provision of additional sensor data. The study provides a profound overview of potential capabilities and limitations of the proposed concept. As replacement, reuse and upgrade of single parts become critical issues when considering the complete product lifecycle, the question on how electronics integration can successfully contribute to a sustainable usage is investigated.
Keywords:
Microsystem, Modular Machine Tool, Sustainable Manufacturing, System Life Cycle

1 INTRODUCTION

Accuracy, productivity and reliability are key attributes of machine tools in order to meet market demands of today's manufacturing environments. Global economic growth is strongly connected to employment and therefore to the wealth of people [1]. More than a quarter of the national output of Germany in 2012 can be attributed to the producing industry [2] and the biggest volume of sales in the engineering sector in 2011 was created within the section of machine tools [3]. Easily reconfigurable equipment meeting high production capacities [4] is evolving into a strongly requested technology to even further stimulate the market and cope with rising production volumes. This is of special concern with respect to flexibility and mobility of modern production systems. Some final products are available in countless possible combinations [5]. Together with shorter innovation cycles, this will lead to a rising need for an even more intensive, efficient usage of machine tools or parts of it.

Previous attempts have been made with the focus on constructing stiff and accurate but passive modular structures like ball-and-rod systems [6]. Those systems tend to be difficult to assemble or lack the required stiffness and dynamic behavior of conventional machine tools. The fundamental approach proposed within this work is to replace monolithic machine tool frames by a set of modular building blocks including active components. Therefore, the system will eventually be able to readjust and eliminate positioning errors. This is achieved through fusion of machine tool structures with micro system technology to bring features of distributed sensing and identification into the single modules, Figure 1. Moreover, active mechanical building blocks being part of the mechanical frame serve as compensating structures to account for static displacements. By integrating autonomous sensors, additional data can be provided to the machine tool's internal control loop resulting in a much higher local resolution to improve working accuracy.

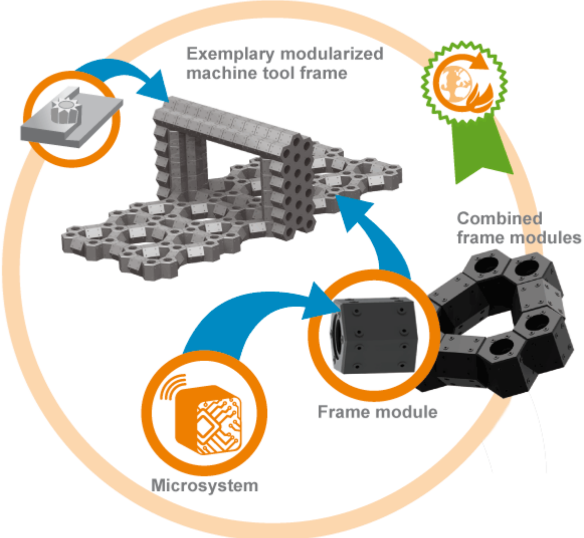


Figure 1: LEG²O concept for milling machine

Along with advanced interconnect technologies for electronics miniaturization comes an increased flexibility towards possible sensing locations and least interference with the mechanical frame, that would otherwise be difficult to obtain with conventional wired sensors. This leads to significant advantages with respect to potential system upgrades in the future, e.g. condi-

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

tion monitoring or modifications as part of the component re-use activities.

This contribution outlines how the proposed concept of modularized machine tools can conduce towards more sustainable solutions whilst meeting market demands. Issues of sustainability have to be tackled on different abstraction levels [7]. First, reduction of environmental impacts directly associated with the technologies and materials is in the focus of research. This comprises the complete life-cycle of the system at a whole. Second, effects on the superordinate system hosting the proposed technological solution need to be taken into account (e.g. effects of micro system technology implementation on energy-efficiency or accuracy of machine tool). On further levels of abstraction substantial influences of revolutionized technology paths on general sustainability issues of manufacturing have to be analyzed. This includes the behavioral changes in machine tool use through technological innovations. Being crucial part of mechanics and electronics design phase, first and second order effects are of primary concern within this work at the current stage. Fundamental requirements towards system design of electronics and mechanics are derived from possible use cases for the proposed concept in order to meet the overall goal of supporting sustainable production.

2 HISTORY OF MODERN MACHINE TOOLS AND LEG²O EVOLUTION

Machine tool systems have evolved rapidly during the last 70 years as a result of various technological developments in the manufacturing world. The study of significant innovations helps to understand the evolution of machine tools with respect to the demand for accuracy and flexibility in the products being manufactured. **Fehler! Verweisquelle konnte nicht gefunden werden.** presents the timeline from the 1940s to the present, demonstrating improvements in achievable machining accuracy along with a broad overview of the developments in production and micro system technology. Achievable machining accuracy is a valid representation of the level of technological advancement of the respective era [6].

The 19th century saw inventions of different machine tools and the development of the basic fundamentals of machining. Until the invention and development of numerical control (NC), most of the machines were controlled mechanically. Competition for products was local and there was no demand for variations in the product [8]. In early 20th century was the start of the automotive industry development and the concepts of mass production and tight dimensions which led to the improvement in the known machines [6]. The automatic control systems developed for military in the Second World War found practical applications in engineering and technology [8]. As a result, numerical control was developed during the late 1940s and 1950s with the help of servomechanisms and punched tapes for input.

With the development of electronic calculators leading to the first electronic computer using vacuum tubes in 1946, a new era for manufacturing began. It is noticed, that the use of computers in the early phases of development of NC machines was considered but because of the high cost of computers, special purpose control units were used instead [9]. Following the concept of NC for machines was the beginning of development of programming languages like APT, the invention of machining centre, expansion of large-scale assembly lines and mass production. After the advent of mini computers in 1960s, computer numerical control was introduced which dramatically affected manufacturing by increased production rates, improved quality and accuracy, more accurate control and easier integration. The 1970s saw the growth in computing power with developments like the programmable logic controller (PLC), first microprocessor by Intel (4004) in 1971 and the beginning of development of

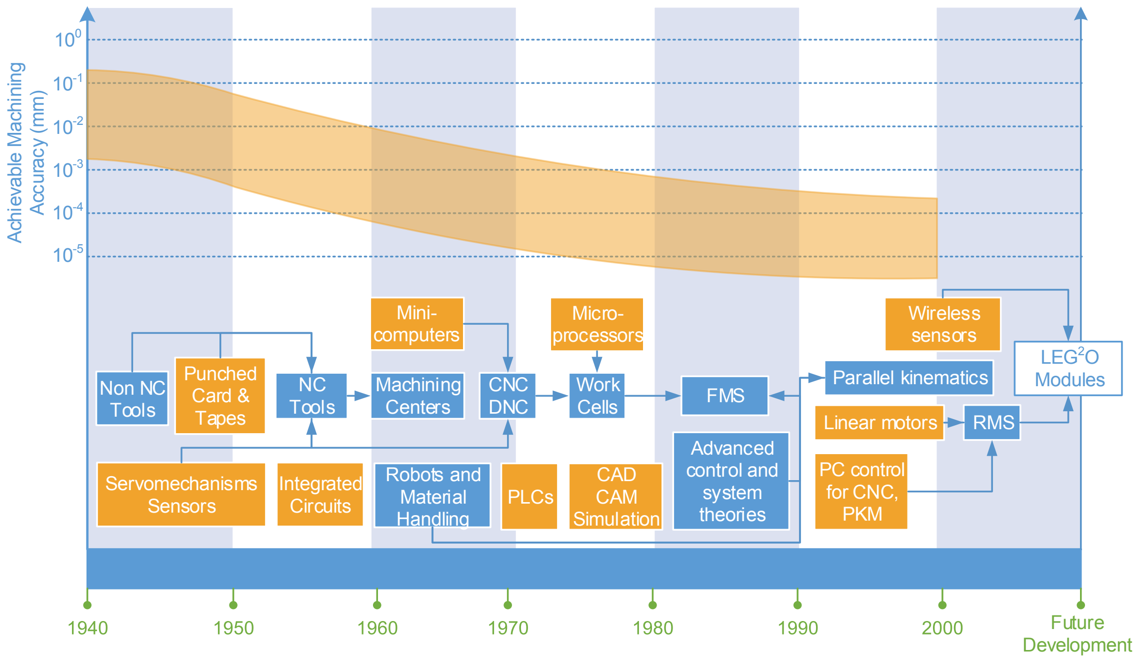


Figure 2: Timeline of machine tool and microsystem technology

geometric modelling and computer aided design and manufacturing (CAD/CAM) techniques [8]. Personal computers (PC) also came into existence through Radio Shack, Commodore and Apple. This development in computing was implemented in manufacturing in the 1980s. Digital control was introduced for peripheral equipment, speciality machines and PCs were used to track the machining parameters along with in-house machinability databases [10].

Mehrabi, Ulsoy and Koren have reviewed the literature regarding the development period of manufacturing technologies and divided it in three epochs viz. pre-CNC (pre-1960s), CNC (1960 - 1990) and knowledge epochs (post-1990) [8]. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows, that the pre-CNC epoch was an era when the fundamentals of machining were developed and the new concept of numerical control was born. This idea of automation proves to be the first node for development of integrated electronic systems into machine tools and leads the way for further research and developments in the CNC epoch (1960 - 1990). Consequently, by the end of that era, the invention of flexible automation or flexible manufacturing systems changed the outlook on manufacturing systems as a whole.

A flexible manufacturing system (FMS) is a machining system with fixed hardware and fixed, but programmable, software to handle changes in work orders, production schedules, part-programs and tooling for different parts [8]. Thus, flexible manufacturing was the first step in giving a degree of freedom to the manufacturing system so that it can be adapted to produce different parts that change over time with required volume and quality. The next development, reconfigurable manufacturing systems (RMS) which focus on modularity, can be seen as the next level of flexibility. Those systems propose a library of machine elements which could be assembled according to the specific requirements.

The last 20 years have been characterized by intense global competition and progress in computer, information technology, management of information systems, advances in communication systems and penetration of computer technology in various fields. This has led to a market of high global competition and fluctuating demands which is reflected in the manufacturing paradigms that are currently being developed.

The introduction of first universally applicable wireless sensor platforms [11], able to operate autonomously with a set of conventional batteries for many years, was a logical consequence of the developments in the microelectronics field during the early 1990s. Integrated circuits had advanced to a degree that power aware routing along with significantly reduced device startup power and improved sleep modes made average power consumption in the microamps range possible. Breakthroughs in micro-electro-mechanical system (MEMS) technology provided sensor concepts, which allowed for hybrid system integration of multiple sensing principles regarding component size, cost and energy requirements. By transferring advanced interconnect technologies onto the class of autonomous microsystems it was shown, that complete functionality (sensing, processing, wireless data transfer, energy supply) would comply with system dimensions in the millimetre-range [12]. These developments along with then available, energy densities of lithium-based batteries and wireless communication standards lead to first commercial applications, e.g. building automatization, of wireless sensor nodes (WSN). WSN were introduced into machine tools in [13] for tool parameter optimization in existing structures. Challenges regarding harsh environmental conditions and prolonged lifetime through energy harvesting from the ambient environment were approached in [14]. Microelectronic condition monitoring systems were adapted to a paper mill with the focus on housing all functional components within a single, wireless system.

Main innovation hubs at the current level of machine tool (MT) and microsystem technology (MST) fusion (MT-MST) can be summarized as follows:

- Distributed sensing of temperature and/or forces at the frame for *accuracy* optimization by contribution of additional data to the control loop of the machine tool
- *Identification* of machine parts and their history in flexible and modular design approaches
- Sensing and/or transmission of consumption related data to improve *efficiency* of manufacturing equipment
- *Additional functionality* through condition monitoring capabilities at selected spots and hardware at locations that are difficult to reach with conventional, cabled sensors and/or at spots that are objected to steady adjustments due to tool reconfiguration.

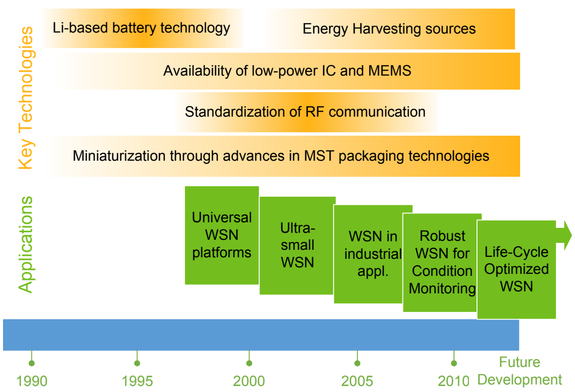


Figure 3: Development of wireless sensor networks (WSN)

Figure 3 comprises the development path described: Now that the implementation of WSN even in harsh environmental conditions has successfully been proven from a technical perspective, strategic research questions concerning their sustainable usage arise. Positive second level effects on sustainability in manufacturing environments (improvements in yield, efficiency and effective usage of equipment) are undisputed and have to be quantified by adequate environmental indicators in further periods of the project. Direct, first level effects of mechanical and micro system parts have to be evaluated against the background of environmental impacts reduction during the complex LEG²O life-cycle. The particular importance for the case of modular machine tools is predicated in the increasing number of potential sensor interfaces and therefore quantity of electronics. Moreover effects of aging, wear and obsolescence have to be considered on different technological levels as these will ultimately determine post production services. Considering the latter already at the design phase of the tool, will contribute to its sustainable usage of the tool along the complete life cycle.

3 ANALYSIS OF USE CASES

3.1 Compatibility of LEG²O with conventional tools

The LEG²O vision is to replace conventional monolithic machine tool frames with microsystem enhanced, universal modules. As every structure can be theoretically approximated, some machine tools benefit less from LEG²O, since their process simply does neither require reconfigurability nor flexibility. In this section, the authors will evaluate the compatibility of the LEG²O concept under consideration of both, feasibility and specific advantages towards conventional machine tools. For this purpose, a comprehensive list of the most common produced machine tools of Germany in 2003 is used to evaluate their compatibility with the LEG²O modules [15]. They divide into cutting machines and forming machines. Data is derived from a broad recherché of current market and the grading bases on the comparison of different machine tools. At the end of the evaluation, adequate use-cases for modular machine tools are discussed on the basis of the tables' grades. The results can be found in Table 1.

Table 1: Comparison of machine tools

		Technical feasibility	Configurations	Accuracy	Flexibility
Cutting machine tools	Electrical discharge machining	+	o	+	o
	Laser-, Ions- and Ultrasonic-MT	+	+	+	+
	Machining center, flexible systems	+	+	+	+
	Transfer machines	o	+	+	o
	Lathe	+	o	+	+
	Drill machine	+	o	o	o
	Boring machine	+	o	+	o
	Boring machine comb. with milling	+	+	+	o
	Milling machine	+	+	+	+
	Sawing and separating machines	o	-	-	-
	Honing and lapping machine	+	o	+	o
	Grinding and polishing machine	+	o	+	o
	Gear cutting machine	+	+	+	o
Forming machine tools	Shearing machine	+	o	o	o
	Punching machine	+	o	o	o
	Corner notcher	o	-	o	-
	Bending machine	o	o	o	o
	Edging machine	o	o	o	-
	Straightening machine	+	+	o	-
	Press	+	+	o	-
	Forging press	+	+	o	-

In Table 1, *technical feasibility* defines the ability of replacing conventional machine tools and building types with LEG²O modules. The grading '+' suggests, that the modules can resemble most parts of the machine tool whilst '-' indicates, that the machine tool requires a high number of application-specific add-ons besides the reconfigurable, standardized modules. Therefore, a high *technical feasibility* implies a good use case for LEG²O modules. C*onfigurations* define the process's demand towards a high degree of possible machine tool configurations, e.g. a milling machine tool has different spindle orientations and hence synergies with the LEG²O approach. *Accuracy* compares the overall tolerances of the named machine tools which are an indicator for feasible usage of the accuracy optimizing strategies like wireless sensor data and active blocks. *Flexibility* is about future demands towards adaption of the modularized machine tool to new product requirements [16]. It motivates efforts to increase intelligence in the single LEG²O modules, i.e. identification, enabling them to be part of a steadily evolving system within the context of global manufacturing environments.

3.2 Results from compatibility analysis and development of use-case scenarios for LEG²O modules

As it can be seen in Table 1, the class of forming machine tools has generally a lower accuracy and flexibility when compared to cutting machine tools. These processes are primarily used for less complicated tasks that do not require high precision tolerances, e.g. punching, bending, edging. Another broad application field is the preprocessing of semi-finished workpieces for later processing like milling or turning. Also there is only a low demand for flexibility considering today's market.

In the field of cutting machine tools, the conditions differ as there is a strong dependence upon the specific cutting process. The trend towards more flexible and productive tools results in a variety of different machines [17]. Cutting as a manufacturing process is separated into six groups which in turn subdivide into 39 sub-categories [18]. Most of the conventional machine tools are specialized in one of the sub-categories but with machining centers, FMS and RMS the foundations are laid for flexible manufacturing systems. As cutting accuracy is directly bound to the tolerances of the machine tool itself, there is a strong need for fitting the requirements of dimensional accuracy and surface conditions in an economic way. The class of cutting machine tools is often distinguished not only in terms of the specific construction, e.g. horizontal or vertical milling spindles, but also in accuracy and processing power. In this context, new terms like high precision machine tools and high performance machine tools have established.

As a result of the comparisons made in Table 1, Laser-, Ions- and Ultrasonic machine tools, machining centers and milling machines tend to be a good use case for the LEG²O frame building set. All mentioned machine tools are highly accurate, flexible and available in different configurations. Furthermore, processes similar to milling like gear cutting or boring as well as lathes provide feasible scenarios.

4 RESULTING SYSTEM REQUIREMENTS FOR MT-MST STRUCTURES

4.1 General requirements towards machine tool layout

In [17] it is mentioned, that the most important task for machine tool frames is the correct positioning of functional parts as well as in loaded and unloaded condition. Therefore, general requirements for machine tool frames like static, dynamic and thermal stiffness exist. Depending on the machining type, the environment and application field, additional demands have to be satisfied.

The LEG²O modules try to adopt the form and functionality of conventional machine tool frames. Therefore, when assembled, they must behave like conventional frames in terms of stiffness and dynamics. Besides operating conditions, machine tool workloads need also to be considered, as they determine local forces and temperatures within the frame.

The blocks themselves can physically resist only limited forces before they exceed the maximal yield stress and deflect permanent or even break. That is why considerations of base metal alloy and geometry of the modules are primarily focused on lightweight, high static stiffness at moderate temperature dependence and dynamic behaviour.

The application field prescribes the basis functionality, which has to be offered by the modules and the periphery. As there are various machining processes applied in modern manufacturing, requirements towards the specific machine tool frames differ significantly from process to process. For example, high precision milling tools need a stiffer machine tool frame than an electrical discharge machine tool or the frame weight of high speed cutting machines must be low due to the dynamic behaviour of the whole structure. To make up a complete machine tool, guidelines, spindles, actuators and more have to be connected to the LEG²O structure. Due to the modular approach, the tolerances of each block add up when it comes to assemble the structure. Additional components like linear guidelines need at least flatness and parallelism of a few micrometers. Therefore, the modules tolerances have to compete with requirements in terms of dimensions, angularity and parallelism.

When it comes to assemble, re-use or exchange of single blocks, the mechanical connections becomes important. Although bolting one block on another is an easy method to make up LEG²O structures, this is rather unfavorable for disassembling. Permanent connections like gluing and welding complicate the reuse and recycling as well. Detachable connections like quick-clamping, magnetic or pneumatic fixing could solve the problem and contribute to easy and time-efficient assembling. The intermediate environment has a major influence on making design choices. As the LEG²O blocks have a maximum weight of 30 kg, there is a great potential for simple manual transportation. Hence, new production strategy like building machine tools near the application field becomes possible. A mobile open-air production is exposed to sun and therefore large deflections result from temperature changes. In a laboratory, the temperature is almost constant and the frame is only deflecting due to the actuators and process temperatures. Dirt might pose challenges to moving parts of the machinery if operated outside a clean machine hall. Other environmental factors such as humidity or moisture require modified surfaces to protect the material from corrosion. Implementation of this new technology could lead to serious drawbacks when considering different locations and backgrounds of service personnel. Along with maintenance provided by the manufacturer of the tool, support for correct assembly, modification and operation should be part of the overall service concept. Besides intuitive design, software-tools could simplify planning and usage of the LEG²O system. Use of MST for in-situ monitoring of module handling (e.g. analysis of three-axial acceleration) and provision of feedback to the worker is another valid option.

4.2 Implementation of micro system technology in modular machine tools

Increased functionality at low costs and minimum back coupling to the superordinate mechanical system is the main motivation for micro system technology implementation into the frame. General criteria describing the requested system functionality as well as the environmental conditions can be directly derived from the requirements catalogue of the machine tool itself. Most common tasks will cover the distributed sensing of temperature values, forces or humidity with strongly varying requirements towards spatial resolution and accuracy. The context of the application (data provision to the control loop of the machine tool, condition monitoring of subsystems or acquisition of tool handling related data) will consequently reduce the set of technical options regarding choice of components, achievable degree of miniaturization and operating time without battery exchanges. Nevertheless, the environment of machine tools provides particular challenges that must not be neglected within system design (Figure 4).

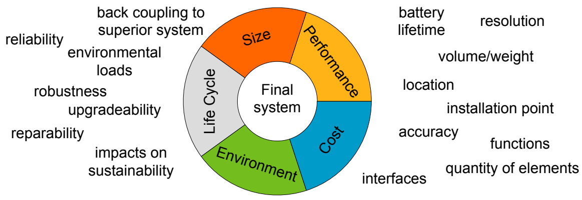


Figure 4: Design criteria for MST in LEG²O modules

Given the particular task of the targeted application, minimization of energy consumption will be the primary focus to prolong wireless operating time. Design decisions will most often be contradictory to further performance criteria, e.g. accuracy, data rates or duty-cycle, which should therefore be carefully chosen to avoid overdesign. Testability, adaptability and modification will become more challenging with every step in the design phase of highly integrated MST solutions. This is due to the nature of application specific realizations for WSN that are tailored to the specific measurement tasks in order to reduce energy demand to a minimum. For a precise definition of micro system functionality in the context of distributed sensing for accuracy optimization, a modular test platform based on commercially available components was implemented. A modular test platform based on commercially available components was implemented. Main components are a 3-axis acceleration sensor for handling support of the blocks and a temperature sensor to access temperature distribution within the frame. Processing is done using an ATmega328. Evaluation of sensing concepts as well as routines for data processing is carried out during the conceptional phase of the LEG²O frame. The system can currently be addressed via Bluetooth or standardized I²C and SPI interfaces for rapid sensor evaluation. Design guidelines for the final demonstrator are then derived from the results of the analysis after coupling of electronics with currently developed prototypical mechanical building blocks.

4.3 Challenges towards sustainable development - Multi life cycle approach

The most crucial aspect in MST design for machine tools evolves from the fusion of two complex technical domains with individual life cycles. Machine tools exhibit use times estimated around 20 years and more [19] in combination with high workloads. Depending on the environmental loads occurring at the specific mounting location these lifetimes might be challenging for WSN. Concepts for electronics condition monitoring in combination with design rules for robust system setup can prolong necessary service intervals. However, interruptions for battery exchange will be necessary in order to achieve adequate system dimensions. Furthermore, MST is objected to explicitly shorter innovation cycles.

A comparison of functional improvement rates for core components in electronics equipment is shown in Figure 5. In addition to effects of aging and wear, aspects of obsolescence need to be considered. Within the targeted lifespan it is rather likely that production of technically superseded components is discontinued. Moreover, supporting technologies within the infrastructure of the device, e.g. wireless communication using standardized protocols, might no longer be available. There will be break-even points for replacement of efficiency improved parts from an environmental point of view that lead to exchanges even before end of life.

The key to sustainable solutions lies in the alignment of measures for repair, exchange or upgrade of MST with regular service intervals of the machine tool structure. Therefore, the ability for multiple modifications of MST during the lifespan of the machine tool (multi life cycle of MST) has to be considered already in the design phase of the system. This includes design for recycling of electronics devices or single functional units, accessibility to mounting locations and removable connections. In terms of upgradability, interfaces between MST and MT need to be precisely defined.

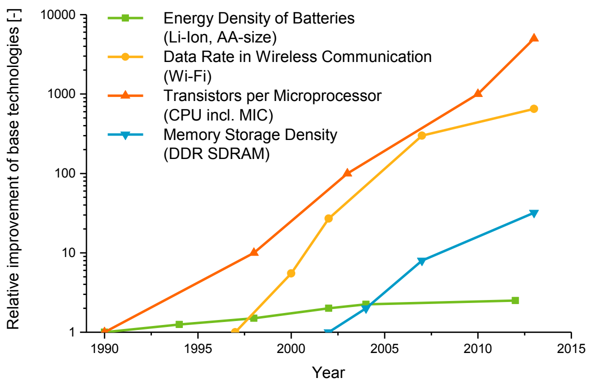


Figure 5: Development rates of microelectronic components

5 SUMMARY

In this contribution, the evolution of the LEG²O concept as a result of latest trends in manufacturing equipment and wireless sensor systems was described. Driven by the need to define adequate use-cases that involve LEG²O equipment, an analysis of compatibility with conventional machine tools was carried out. The identification of possible applications for modular machine tools will lead to a further concretization of requirements towards the prototypical implementation of the proposed concept. However, from analysis of the special class of wireless sensor systems wedded to machine tool frames, a core set of general criteria for system layout was identified. Beside the technical realization of distributed sensing in LEG²O modules, main focus lies on the development of routines for sustainable implementation of MST-MT structures in the context of aligning multiple life cycles of its subsystems.

6 ACKNOWLEDGMENTS

This work was funded by the Deutsche Forschungsgemeinschaft (German Research Foundation) within the Collaborative Research Centre (SFB) 1026.

7 REFERENCES

[1] Chryssolouris, G., 2005, Manufacturing Systems: Theory and Practice, Springer.

[2] Statistisches Bundesamt, 2013, Bruttoinlandsprodukt 2012 für Deutschland.

[3] Statistisches Bundesamt, 2012, Werkzeugmaschinen in Deutschland, Statista Dossier.

[4] Brecher, C., 2011, Integrative Produktentwicklung in Hochlohnländern, Springer.

[5] Wagenitz, A., 2007, Modellierungsmethode zur Auftragsabwicklung in der Automabilindustrie, Dissertation Univ. Dortmund.

[6] López de Lacalle, L. N., Lamikiz, A., 2009, Machine Tools for High Performance Machining, Springer.

[7] Berkhout, F., Hertin, J., 2001, Impacts of Information and Communication Technologies in Environmental Sustainability: speculations and evidence, Report to the OECD.

[8] Mehrabi, M. G., Ulsoy, A. G., Koren, Y., 2000, Reconfigurable manufacturing systems: Key to future manufacturing.

[9] Ferguson, N. C., 1978, A history of numerically controlled machine tools, CME.

[10] Technical Timeline: 50 years of manufacturing technology, 2005, Cutting Tool Engineering.

[11] Hill, J. L., Culler, D. E., 2002, MICA: A Wireless platform for deeply embedded networks", IEEE Micro 22, no. 6: 12-24.

[12] Lang, K. D., 2005, Industrially compatible PCB stacking technology for miniaturized sensor systems.

[13] Dornfeld, D., Wright, P., 2007, Technology Wedges for implementing green manufacturing, Transactions of NAMRI/SME, Volume 35.

[14] Benecke, S., Ruckschloss, J., Nissen, N.F., Lang, K.-D., 2012, Energy harvesting on its way to a reliable and green micro energy source, Electronics Goes Green 2012+ (EGG), vol., no., pp.1,8, 9-12 Sept. 2012.

[15] Weck, M., 2005, Werkzeugmaschinen: Maschinenarten und Anwendungsbereiche, Springer, VDI.

[16] Perovic, B., 2006, Handbuch Werkzeugmaschinen: Berechnung, Auslegung und Konstruktion, Band 10, Hanser Verlag.

[17] Perovic, B., 2009, Spanende Werkzeugmaschinen: Ausführungsformen und Vergleichstabellen, Springer.

[18] DIN 8580:2003-09: Fertigungsverfahren – Begriffe, Einteilung, 2003, Beuth.

[19] Energy-using Product Group Analysis, 2011, Lot 5: Machine tools re lated machinery, Fraunhofer IZM.

[20] Paradiso, J., Starner, T., 2003, Energy Scavenging for Mobile and Wireless Electronics, IEEE Pervasive Computing, Bd. 4, Nr. 1, IEEE Educational Activities Department

[21] Group, C. W., & Systems, E. A., 2009, Energy Autonomous Systems: Future Trends in Devices, Technology, and Systems, CATRENE Working Group on Energy Autonomous Systems pp. 1–84.

GCSM 11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

18.3 Human centric automation: Using marker-less motion capturing for ergonomics analysis and work assistance in manufacturing processes

The Duy Nguyen[1], Martin Kleinsorge[1], Aleksandra Postawa[2], Kirana Wolf[3], René Scheumann[3], Jörg Krüger[1], Günther Seliger[2]

[1] Department of Industrial Automation, Technische Universität Berlin, Germany

[2] Department of Assembly Technology and Factory Management, Technische Universität Berlin, Germany

[3] Department of Environmental Technology, Technische Universität Berlin, Germany

Abstract:

Manual labour is still an essential factor for industry. However, work can be physically demanding causing absence through musculoskeletal issues. Moreover, production processes appear to be highly complex causing stress and production errors due to mental fatigue. Methods of human centric automation tackle these problems using automation technology to assist workers. In this paper, we propose marker-less motion capturing to automatically analyse the worker's motion and ergonomics during manufacturing processes. With the information acquired, robots can assist workers to not only meet health demands, but also reduce labour costs and increase the worker's social welfare. Production errors can be reduced by giving situational feedback and guidance based on the worker's motion. We present a first implementation using the Microsoft Kinect® system and propose hypotheses concerning possible social, environmental and economic impacts on semi-automated production, which shall be proven.

Keywords:

Human Centric Automation (HCA); Lifecycle Sustainability Assessment; Sustainability Indicator; Manufacturing Process

1 INTRODUCTION

1.1 Problem Statement

Despite a high degree of automation, assembly and disassembly tasks in industry often depend on manual labour.

Firstly, disassembly and repairing are examples of tasks which have not been planned within a complete product life cycle, so far. The steps to be executed highly vary for each unit to be repaired such that using specialised automatisation devices would result in high costs and a low occupancy rate. Therefore, human workforce is needed for such flexible assembly. Secondly, investing in full automation does not pay off for small lot-sizes or a high number of product variants requiring high flexibility in production [1]. Finally, there are tasks which demand high sensormotoric or cognitive skills which no automated system can fulfil. In brief, human workers are vital due to their flexibility, cost-efficiency and unique skills.

Unfortunately, these tasks can contain situations with high physical load on the worker. According to a German health insurance “AOK” more than one third of the total worker absence in 2009 was caused by musculosceletal complaints or injuries [2]. To reduce physical load, collaborative robots can help. Robots integrated into the workplace can execute physically demanding tasks in the production process on behalf of the human worker or at least simplify them.

Another problem is that complex or monotonous tasks can cause fast mental fatigue resulting in stress at work, reduced performance and production errors. Mental fatigue and stress can be decreased by monitoring systems which guide and supervise workers in their tasks. Employee information systems aggregate all information regarding a work process and present it to the worker in a clear manner. During assembly process, the worker is monitored and guided which leads to a feeling of relief and a reduction of production errors.

We propose Human Centric Automation (HCA) concepts to approach these aforementioned problems. The idea is to use automation technology, in our case robots and optical sensor systems, to assist workers in in their tasks instead of replacing them. We propose to apply them in cases where human workforce is irreplaceable. Recent advances in marker-less motion capturing technology provide the foundations for the solutions presented in this paper.

To ensure that such scenarios improve the workplace area and provide long-term benefit for employers as well as for operators, we analyse HCA by methods of sustainability assessment like the life cycle sustainability assessment.

Therefore, it is needed to elaborate suitable indicators in order to address the pressure and the response on the workers as precise as possible. The enhancement of individual response can be quantified to ensure good working conditions and reduce economic costs (e.g. higher productivity of the worker) as well as environmental burden (e.g. unnecessary waste).

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

In this paper, we intend to address these two problems mentioned above with focus on the application as well as the impacts related to the HCA.

1.2 Related Work

Motion Capturing Systems

Motion capturing systems record the subject's movements while performing arbitrary motions. Typical areas of usage are animating characters in animation movies and video games or analysis of movement for sports or medical purposes. In general, there are three types of motion capturing systems: marker-based, marker-less and non-optical motion capturing.

Marker-based systems, such as Vicon motion capture systems, rely on markers attached on predefined locations on the subject. The markers are designed to be easily detectable by a camera system. Using these markers, the software is able to locate particular parts of the body and precisely reconstruct motions. However, the markers can limit the subject's range of movement. As a result, the recorded motion can differ from the subject's motion without markers. Another disadvantage is that marker-based systems require a user calibration step where the user has to manually define which marker belongs to which part of the body. This can lead to a long preparation time. Besides, the markers may slip during a recording session decreasing precision.

Marker-less motion capturing systems, in contrast, do not need markers. Example products are OrganicMotion OpenStage® and Microsoft Kinect®. The former addresses professional users - especially in entertainment industry - and works on multiple colour cameras. The latter addresses the consumer market and only relies on a single depth camera. User calibration in marker-less systems only consists of adopting a predefined calibration pose for several seconds. Sometimes, it is even not necessary. On the other hand, marker-based systems generally outperform marker-less approaches regarding precision. Marker-less motion capturing systems also often pose strict limitations on the environment. OpenStage expects the tracking area to be closed by white walls and green or white flooring. Additionally, the space must not be obstructed e.g. by a table [3]. The Kinect requires capturing the subject from the front side. Also, objects which partly occlude the view on the subject often heavily affect precision.

Non-optical motion capturing systems, such as Xsens systems, require the subject to wear inertial or flex sensors. These sensors measure mechanical variables such as acceleration and flexion of particular parts of the body. Cameras and image processing systems are not required making the system insusceptible to obstructed scenes and optically varying environment. The trade-off is that the sensors only measure data relative to the last time step. Absolute positions to locate the subject in space have to be computed from an initial pose. However, measurement errors in each time step can accumulate leading to big absolute errors. Non-optical motion capturing devices also limit the range of movement and require an extensive user calibration step.

Despite, its recent limits, we believe that marker-less motion capturing is becoming increasingly important, since it enables workers to naturally execute their tasks without limitations in movement. As this is a highly active field of research, we expect improvements in terms of precision and robustness in the next years.

Automatic collaboration and assistance in manufacturing

Since the field of automatic collaboration and assistance in manufacturing is broad, we concentrate on the overviews on human-robot cooperation and employee information systems. These two fields are related to the application scenarios presented in this paper.

Krüger et al. [4] gives an extensive overview over recent advances in human-robot cooperation in assembly. The paper also outlines the economic potential of such a technology. There has been a lot of research in this field, especially concerning safety issues. First systems have been developed, but more sophisticated and practically useable solutions are to be expected in the next years. We believe that a lot of potential lies in developing concepts to not only reduce costs (economic dimension), but also improving worker's health (social dimension).

Concerning employee information systems, several solutions have been released on the market: Bott and Armbruster Engineering present an assembly workplace for worker qualification [5, 6]. The system consists of a computer and a touchscreen which displays the next work step after confirmation of the current one by the worker.

There are also several methods to automatically recognise the current work step making it possible to alert the worker in case of incorrect task execution. The ultrasonic marker-based 3D tracking system AssyControl from Otto Kind AG tracks hand positions during work. Work steps can be identified by analysing hand trajectories. In cooperation with SKODA the multi sensor based “Wearable-Activity-Tracking” has been developed. Multiple sensors are integrated into the worker's overall. Work step recognition is done by matching sensor profiles to the ones of exemplary work routines [7]. In addition, software has been developed to visualise each step in the assembly process. Process relevant information is shown as text, picture, video or lights attached to fixed positions.

Marker-less motion capturing can improve these solutions, since the hand tracking does not limit freedom of movement. Besides, images of work steps can be captured by a camera which enables to easily create a documentation of the process.

Sustainability Indicators

Sustainability indicators consider all three dimensions of sustainability inclusively and do not focus on the environmental issues alone. Especially environmental indicators have been widely employed for many years, sustainability indicator frameworks are transferred more and more into practice. The first indicators were developed in early 1970 by biologists to describe the health status of an ecosystem. In 1972 the report “Limits to Growth” of the Club of Rome pointed out that continued growth creates stress to the boundaries of our system earth, which can be seen as a first step to think about sustainability [8].

Nevertheless, the most common interpretations of sustainability nowadays are still based on the environmental aspects only. This has its origin partly in political debates starting in the late 1980s and the resulting environmental regulations. Take the aspect climate change as an example: More or less, the whole discussion is on environmental issues and its effect on human kind. Nevertheless, this topic has the potential to include the social and economic dimensions, e.g.include the payment for the changes (how much and by whom) or be aware of the social consequences.

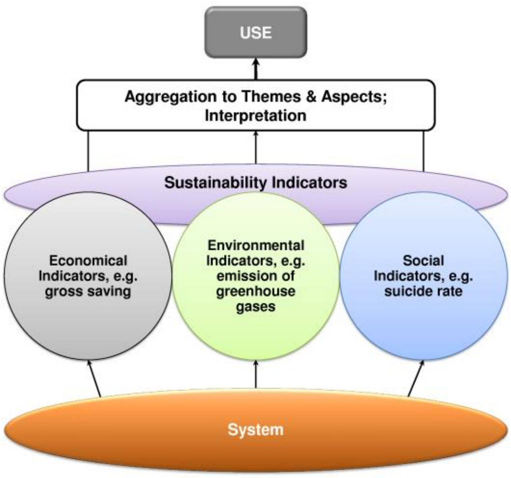


Figure 1: Description of the functionality of sustainability indicators [9].

For a system analysis, e.g. human centric automation the first step is the collection of relevant information (as shown in Figure 1), before the results can be interpreted to make reasonable use in terms of decisions toward a sustainable development.

1.3 Contribution

The contributions to sustainable manufacturing of this study are:

- presentation of application scenarios based on marker-less motion capturing systems to improve work conditions,
- qualitative evaluation of first implementations based on the Kinect system,
- provision of a framework to evaluate the application scenarios concerning environmental, economic and social impacts

2 METHODS

2.1 Motion Capturing System

For our first implementations, we have chosen the Kinect sensor. With its price of about 200 Euros and existing application software ready to be used, the Kinect system enables us to quickly realise a cost-efficient prototype.

The Kinect sensor (see Figure 2) unifies microphones, infrared (IR) camera, colour camera and depth camera. Using the latter, images containing 3D information can be recorded. Each pixel in a depth image denotes the distance from the Kinect device to the nearest object (see Figure 3 right). Depth image generation is done by projecting an IR pattern onto the scene. The distortion of the pattern provides information about the 3D structure of the scene. Since the IR pattern is invisible for colour cameras, there are no scene effects in the colour images.

Figure 2: The Kinect sensor and its components.

There are several software packages which implement marker-less motion capturing algorithms on Kinect depth images. We use the Primesense NiTE™ middleware library from the OpenNI® framework as it offers a platform-independent solution with low computational costs. The software computes absolute joint coordinates given a depth image.

The advantages of the solution are its low costs and that it does not require any user calibration. However, the subject can only be captured from the front perspective. This means in all recordings, the subject has to face the camera device. If the person to be captured turns away, the system may fail to track the motion. To solve this problem, multiple cameras can be used to capture the subject from different perspectives. Unfortunately, it is not possible to use multiple Kinect devices around the subject to always ensure a front view. The projected IR patterns would interfere with each other resulting in even worse depth information quality. Moreover, the system does not work well in case the subject is not completely seen e.g. when a table blocks the view.

In the long run, we plan to implement a motion capturing system based on multiple colour cameras similar to OpenStage to avoid the limitation of perspective.

Figure 3: Left: Colour image of a subject. Right: Depth image and the tracked skeleton. The system draws the back bone and the right arm in red since they represent two examples of ergonomically unfavourable poses.

2.2 Sustainability Indicators and Assessment

Published sets of indicators are taken from e.g. the German Strategy on Sustainability [10, 11], Global Reporting Initiative [12], World Development Indicators [13], International Human Development Indicators [14] or the indicators from the UN Conference of Sustainable Development [15]. They are taken to bridge the manufacturing network with the goal to identify, measure and create a set of suitable indicators for human centric automation.

The indicators are compared to identify duplicates and in order to match them with the demands of the workplace surroundings. A matrix needs to be established with the relevant processes (production, work assistance as well as HCA) in a vertical column and the indicators in a horizontal line. If the process can be measured with the proposed indicator the intersection point will be marked and taken to track the possible development, i.e. the changes on the worker, on the product quality and on the amount of waste.

Afterwards the identified indicators have to be grouped according to the DPSIR framework (introduced and elaborated by the European Environmental Agency [16]. They propose five types of indicators as shown in Figure 4: (i) driving force indicators, (ii) pressure indicators, (iii) state indicators, (iv) impact indicators and (v) response indicators. The driving forces are the forces on an environmental change (e.g. industrial production) by the socio-economic and socio-cultural human activities. The pressures mark the burdens on the environment (e.g. discharges of waste water) by human activities. The state indicators can be used to describe the condition of the environment. The impacts stand for the potential effects of environmental degradation and the response indicators gauge required progress in response of society and government.

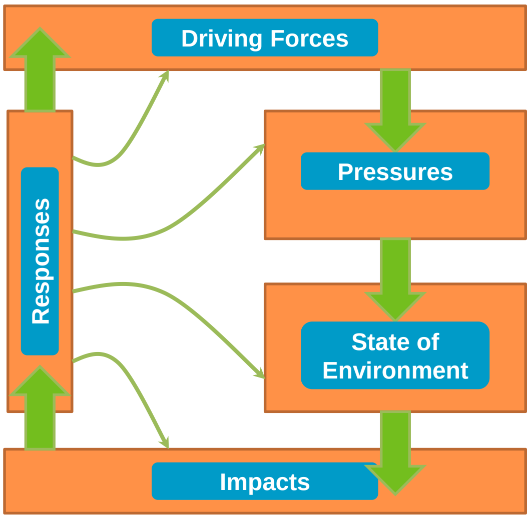


Figure 4: The DPSIR Framework, based on [16]

Finally, according to the implementation of human centric automation indicators are chosen on an exemplary level to show the applicability and to judge the results in terms of supporting decision makers. Hence, a life cycle sustainability assessment can be used as a method to calculate the impact of human centric automation for some quantified indicators.

3 APPLICATIONS

3.1 Ergonomics Assessment

Ergonomics assessment has become a vital component in factory and process planning to ensure health and safety at work. Monitoring tools, such as EAWS [17] have been developed to evaluate processes and workplaces after ergonomic aspects. The overall principle is that load points are assigned for unfavourable physical workload e.g. awkward upper limb or hand poses and handling heavy objects. Finally, the load points are accumulated to determine a final score. These results can be used for risk assessment, planning or redesign of workplaces.

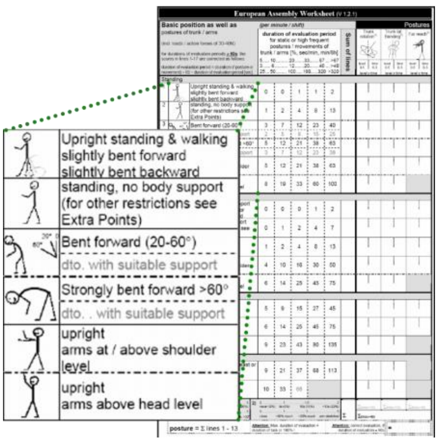


Figure 5: Second page of the EAWS (basic postures).

Automatic ergonomics assessment would provide human robot cooperation systems with essential information.Based on the ergonomics score computed in each situation, the robot is able to decide whether to assist or not and how to assist. Härtel et al. [18] implemented the EAWS using marker-based motion capturing and inertial sensors. We intend to develop a similar system by means of marker-less motion capturing. Our first implementation computes the EAWS basic posture score (see Figure 5) for a process recorded by a Kinect device. We use the 3D limb coordinates provided by the motion capturing system in order to compute joint angles. Using these angles, our system automatically classifies the posture in each image. The overall duration the subject stays in each posture is accumulated in order to acquire detailed statistics. Based on these posture statistics, posture scores from the EAWS sheet can be calculated (see Figure 6).

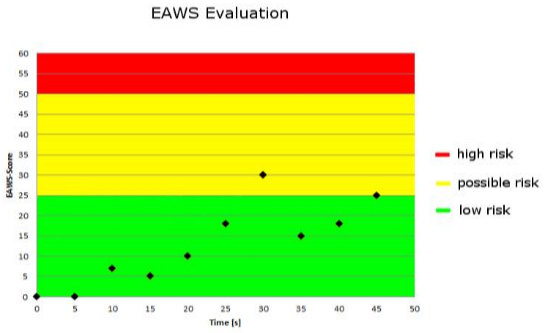


Figure 6: EAWS score of a process computed over time.

3.2 Employee Information Systems

We have developed an employee information system for the guidance of process execution and for worker qualification (see Figure 7). Manual work steps are recognized through marker-less hand tracking with a 3D Time-of-Flight (TOF) camera [19]. The trajectory of the hand and its movement are analysed by MATLAB software.

Over a user interface, work place information is stored in a knowledge base. Based on the content of the workers' hand and its position, work steps like pick, place or the use of objects are automatically recognised. The system creates a work description of the process as well as an analysis based on the method of time measurement UAS[20]. The analysis can be used for documentation as well as basis for system optimisation.

Besides, images from the tracking process are used for visualisation of the task. Based on the work description, text is automatically displayed to describe the work step more in detail and to guide the worker (see Figure 8 left).

We plan to provide the worker with a feedback regarding a incorrect work step and tell what to do instead. With the developed system workers can be passively guided through the display of a work description or actively through the feedback system. This range of options allows a worker qualification related guidance. The worker's stress conditioned by complicated tasks or a low work routine can be reduced. The number of errors can be decreased.

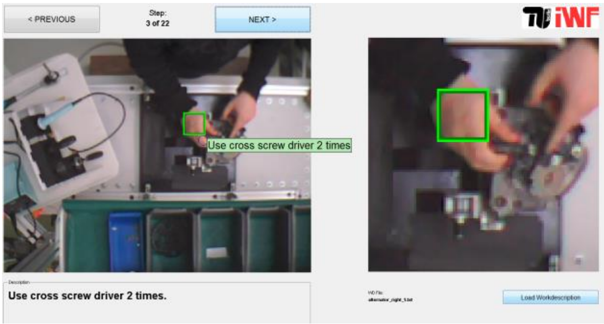


Figure 7: Our implemented employee information system.

3.3 Robots supporting workers

Using the ergonomics score, especially physically intensive tasks in a process can be identified. Examples are: moving heavy loads or working in awkward postures for a long time.

Robots at workplaces can support the worker. In the first case, the robot could execute the task on behalf of the worker. In the second example, the robot could change working conditions to reduce physical load e.g. by turning and moving the object to be processed such that the worker can work in a "ergonomically better" posture (see Figure 8). For a more cost-efficient configuration, also lifting tables tables with a rotating socket can be used.

The robot has to apply to human robot collaboration safety standards to be able to join work without effecting efficiency or colliding with the worker. Solving this challenge would involve recognising the current work step from observations which should trigger the robot planning assistive actions as soon as the ergonomics score exceeds a threshold.

We plan to tackle this concept of collaboration in subsequent works.

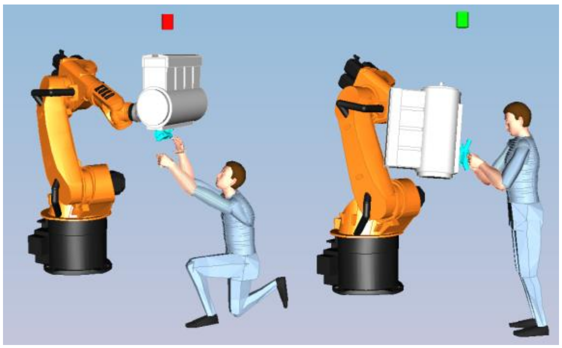


Figure 8: Example of human-robot cooperation. The system automatically detects an unergonomic work pose (left) and makes the robot adjust the object such that the worker can adapt a more ergonomic pose (right).

4 DISCUSSION

In this section, possible environmental, economic and social impacts of the aforementioned application scenarios are discussed. At first, the assumptions were derived for the case of the German industry to address exemplary circumstances which e.g. help to compensate demographic effects in Germany. Later the results shall be transferred to more application, if possible in combination with a change of the regional context.

4.1 Integration of the System into a Workplace

The final system (without robot) consists of a high performance computer and a set of cameras. In order to integrate the system into an existing workplace, the cameras have to be placed in a way that the worker is visible from all perspectives. Afterwards, the camera system has to be calibrated, which means the exact positions of the cameras in space have to be determined. Calibration process will possibly take some minutes and has to be done every time camera positions change.

The system operates in energy saving mode until a subject is detected. In case the worker is seen by the cameras, the system switches to tracking mode activating more computational power. At the moment, we estimate the maximum power consumption of our prototypical system at 1.5kW (1.4kW computer, 100W cameras and display). However, it has to be considered that maximum utilisation is only achieved when the worker is being tracked. Furthermore, we expect the end product to be less power consuming, since the system as such can be optimised in terms of energy usage. It might be even possible that the computer handles the cameras of more than one workplace.

4.2 Possible Environmental Impacts

Clearly, equipment consisting of high performance server and cameras will lead to a reasonable amount of Cos emissions due to higher energy consumption. According to the energy 5.0 specification the total required power consumption results from the operational mode weighting with an off phase of 35% a sleep phase of 10% and an idle phase of 55% [21]. That would mean that the prototype consumes around 20 kWh/d (18.5 kWh/d = server, 1.56 kwh/d camera and display). The electricity consumption results in the emission of 11.3 kg CO_2e. with the German energymix emission factor from the year 2010 [22]. What has not been considered yet is the emissions related with the production of the system as well as with the end of life scenario. Additional studies on that topic will be carried out as soon as the prototype is ready for trial applications to verify the reduction of errors by technical assistance and process education.

4.3 Possible Social Impacts

On the one hand, camera based technology involves dealing with data security and privacy issues. Questions, such as anonymisation of workers and data retention policies have to be discussed. Furthermore, working on camera surveillance can cause feelings of discomfort and anxiety among workers reducing their performance. Finally, robot-human cooperation involves dealing with safety issues. New cooperation systems have to fulfil norms, such as “ISO 10218: Robots for industrial environments – Safety requirements” in order to be allowed in practical use.

On the other hand, worker's health and therefore wellbeing can benefit, since physically demanding tasks can be assisted by robots leaving tasks with low physical load to the human. Assistance systems can also monitor and guide the process helping workers to feel supported during complex tasks and relieving stress. Since we expect an improvement in work performance through assistance, it may be likely that employers now tend to invest more in flexible semi-automation instead of full-automation. Thus, instead of cutting jobs because of automation technology, unemployment rate can be reduced due to improved human performance. Finally, using these systems for qualification can help to improve training. Concerning demographic development in Germany, qualification systems can compensate the loss of experienced trainers due to retirement.

4.4 Possible Economic Impacts

It has to be considered that the introduction of such systems involves reasonable costs. Firstly, it probably costs around 100,000 Euros (excluding robots) to install and operate such a system on an existing workplace. Using 10 professional industry cameras instead of the Kinect device leads to costs of about 30,000 Euros. The processing of such a huge load of image information requires a high performance computer of about 15,000 Euros. The rest of the budget remains for the costs of the ergonomics assessment and robot control software.

In contrast, we believe that these costs will pay off, since higher productivity reduced amount of junk will result in higher margins. Moreover, a lower worker absence rate will reduce the loss for company. In an example calculation, Krüger et al. [4] states that under special circumstances an invest in hybrid workplaces can pay off in less than one month with a reduction of production costs of 58%. If we consider a macroeconomic view, the state will benefit as well, since health expenses can be reduced and more elder people are enabled to work resulting in more taxes as well as reduced social welfare payments.

5 CONCLUSION & OUTLOOK

We have presented solutions including implementations to improve work conditions using methods of human centric automation. Moreover, we provide a first step regarding sustainability assessment of these application scenarios.

Our future works include improving motion capturing technology, developing interaction concepts for human-robot cooperation and installing a trial application in a real factory surrounding.

ACKNOWLEDGEMENT

We gratefully acknowledge the funding of this work by the German Research Association (Deutsche Forschungs-gemeinschaft, DFG), Collaborative Research Center CRC1026 (Sonderforschungsbereich SFB1026).

REFERENCES

[1] Bley, H., Reinhart, G., Seliger, G., Bernardi, M., and Korne, T., Appropriate human involvement in assembly and disassembly. CIRP Annals-Manufacturing Technology, 2004. **53**(2): p. 487-509.

[2] Badura, B., Schröder, H., Klose, J., and Macco, K., Fehlzeiten-Report 2010: Vielfalt managen & Gesundheit fördern: Potenziale Nutzen Zahlen, Daten, Analysen aus allen Branchen der Wirtschaft. 2010: Springer DE.

[3] Organic Motion, openstage Realtime Markerless Motion Capture. 2012.

[4] Krüger, J., Lien, T.K., and Verl, A., Cooperation of human and machines in assembly lines. CIRP Annals-Manufacturing Technology, 2009. **58**(2): p. 628-646.

[5] Bott, Armbruster Engineering: Gesamtpaket Montagearbeitsplätze mit Werkerführung, handling Heft 1/2. 2012.

[6] Armbruster Engineering, Werkerführung an Montagearbeitsplätzen.

2010.
[7] Stiefmeier, T., Roggen, D., Troster, G., Ogris, G., and Lukowicz, P., Wearable activity tracking in car manufacturing. IEEE Pervasive Computing, 2008. **7**(2): p. 42-42.
[8] Meadows, D.H., Meadows, D.L., Randers, J., and Behrens III, W.W., The Limits to Growth, ed. Rome, C.o. 1972, New York, NY: Universe Books.
[9] Scheumann, R., Fügenschuh, A., Schenker, S., Vierhaus, I., Borndörfer, R., and Finkbeiner, M. Global Manufacturing: How to Use Mathematical Optimisation Methods to Transform to Sustainable Value Creation. in 10th Global Conference on Sustainable Manufacturing. 2012. Istanbul.
[10] Bundesregierung, Perspektiven für Deutschland - Unsere Strategie für eine nachhaltige Entwicklung. 2002: Berlin.
[11] Bundesregierung, Nationale Nachhaltigkeitsstrategie - Fortschrittsbericht 2012. 2012: Berlin.
[12] GRI, Sustainability Reporting Guidelines. 2011, Global Reporting Initiative: Amsterdam, Netherland.
[13] WorldBank, World Development Indicators 2012. 2012, Washington D.C.: World Bank.
[14] HDR, Human Development Report 2013 - The Rise of the South. 2013, United Nations Development Programme: New York City.
[15] UN-DESA, Indicators of Sustainable Development: Guidelines and Methodologies. 2007, United Nations: New York.
[16] EEA, Environmental indicators:Typology and overview in Technical Report No 25/1999. 1999, European Environmental Agency.
[17] Schaub, K., Caragnano, G., Britzke, B., and Bruder, R., The European assembly worksheet. Theoretical Issues in Ergonomics Science, 2012(ahead-of-print).
[18] Härtel, T., Keil, A., Hoffmeyer, A., and Toledo Munoz, B. Capturing and Assessment of Human Motion during Manual Assembly Operation. in First International Symposium on Digital Human Modeling, Conference Proceedings. 14-16 June 2011. Lyon, France.
[19] Postawa, A.B., Kleinsorge, M., Krüger, J., and Seliger, G., Automated image based recognition of manual work steps in the remanufacturing of alternators, in Advances in Sustainable Manufacturing. 2011, Springer. p. 209-214.
[20] Bokranz, R., Landau, K., and e.V, D.M.T.M.V., Produktivitätsmanagement von Arbeitssystemen - MTM Handbuch. 2006, Schäffer-Poeschel Verlag.
[21] European Commission, Commission Decision of 16 June 2009 in regards to the coordination of energy-efficiency labelling programmes for office equipment on the revision of the computer specification in Annex C, part VIII, to the Agreement 2006/1005/EC. 2009, EC: brüssel.
[22] Umweltbundesamt, Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010. 2012, FG I 2.5 Energieversorgung und -daten: Dessau-Roßlau.

18.4 The potential of reducing the energy consumption for machining TiAl6V4 by using innovative metal cutting processes

E. Uhlmann [1], P. Fürstmann [1], B. Rosenau [1], S. Gebhard [1], R. Gerstenberger [1], G. Müller [2]
[1] Institute for Machine Tools and Factory Management, Technische Universität Berlin, Germany
[2] Institute for Production Systems and Design Technology, Fraunhofer IPK, Germany

Abstract
Small and medium-sized production companies are alarmed at the increasing costs for energy. There are two possibilities presented to decrease the energy consumption per produced part. The first approach of energy saving refers to turning TiAl6V4. For this, the energy demand of machine tool, cooling system and tool wear of an internally cooled turning tool with closed cooling circuit at dry and wet machining and at combined cooling were compared. It becomes obvious that the turning tool allows for an enormous energy saving potential as well as for lifetime advantages or productivity increases respectively. The second energy saving approach investigates the milling of TiAl6V4 workpieces. In this case, a machine tool's energy consumption during conventional milling was compared to the energy consumption during a trochoidal milling process. It is described that a trochoidal milling strategy offers considerable potential for improvement as regards energy consumption and process time.

Keywords:
TiAl6V4; Energy Consumption; Energy Efficiency; Internally Cooled Tool; Trochoidal Milling

1 INTRODUCTION

Currently, the demand for shorter and shorter product life cycles and customisation leads to a more flexible use of machine tools. That means that machine tools have to cover more and more requirements of the production process. At the same time, the production shall be as energy efficient as possible in order to minimize the variable costs. In order to meet these requirements, the machine tool, the tool and the production strategy would ideally have to be adjusted to every single task. As such an adaptation is hard to realise in an operational environment in many cases and as it is often uneconomical, new tool systems or cutting strategies might help to reduce the energy consumption at increased productivity of the machine tool.

The energetic efficiency of the metal cutting process depends on the following factors: machine tool, cutting process and tool. The two last-named factors can be amended fast and inexpensively without a high capital commitment.

The material investigated in this paper is a Ti alloy grade 5, TiAl6V4. This Ti-alloy has a considerable economic influence with its market share of 50 % and is, at the same time, the most widely used Ti-alloy. This light metal is especially used by the aerospace industry as its characteristics of a high temperature resistance and a low density of 4,43 g/cm^3 at high tensile strength of R_m = 1060 N/mm² complement each other positively. The last-mentioned value decreases with increasing temperature so that TiAl6V4 can usually be used until 315 °C without any risk. Due to its high corrosion resistance as regards hot fluids, this material is frequently used for turbine manufacturing. Ti alloys embrittle at temperatures above 700 °C due to titanium's high affinity for oxygen and nitrogen. At high material removing rates or a high speed of cutting, this effect leads to unwanted subsurface damages. Together with the low head conductivity and with the reactivity with oxygen, the light metal reacts exothermic at high cutting temperatures. Therefore, the process should be cooled well whenever Ti alloys are cut. Due to their increasing importance, the efficient and productive machining of titanium looms larger and larger in the area of production technology as quite often more than 80 % of the unmachined workpiece are cut [1, 2, 3, 4].

2 POTENTIAL FOR ENERGY SAVINGS

During the manufacture of rotationally symmetric parts made of TiAl6V4 there are not many possibilities to increase the energetic productivity. In the case of heavy machining it is possible that, for example, several cutting edges / tools are used simultaneously, whereas the surface quality is critical for the quality in the case of fine machining and, thus, defines the process parameters. One possibility to lower the energy consumption per machined workpiece in the case of fine machining, is to substitute one main consumer of the machine tool, e. g. the cutting liquids supply [5, 6]. In the industry, the cutting zone is cooled by cutting liquids (CL) when Ti alloys are cut. Additionally, minimum quantity lubrication systems (MQL) are used together with tools with wear protection coating geared to these. Another cooling strategy is the dry machining [7] that, however, should be avoided for tools that are not geared to the cutting process as they show a high tool wear. Nevertheless, the downstream, energy-intensive cleaning process of the workpiece can be spared in the case of dry machining and the chips can be disposed of

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

immediately without any follow-up treatment. Internally cooled tools (ICT) with closed internally cooling circuits are a further possibility of tool cooling [8]. They have a coolant circulating within the tool to reduce the temperature of the cutting edge as much as possible.

Milling operations offers higher energy saving potentials compared to turning operations. This is as in most cases a reduction of process time leads to energy savings. If a complex surface roughness is produced, energy can e. g. be saved by the optimisation of the travel length [9]. Less complex 2.5-D geometries often have milling algorithms predetermined by the machine that leave little margin for time savings. One approach can be found in machine tools with a high axis dynamic. With them, trochoidal process can be executed. A trochoidal process differs from a conventional milling process as the tool does not only make a feed movement towards the processed material but additionally a circular movement, see figure 1.

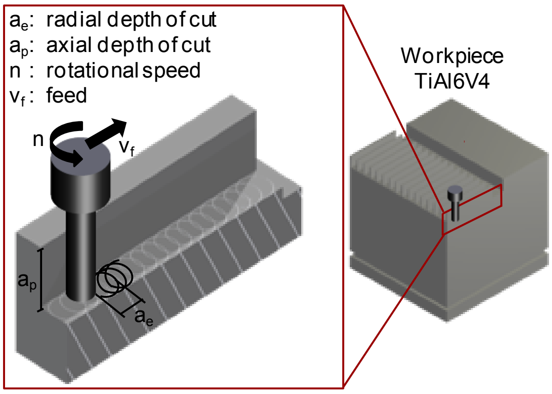


Figure 1: Kinematics of the trochoidal milling process

This leads to the fact that the radial depth of cut varies and that the wrap-around angle can be adjusted variably at the tool. In the case of conventional slot milling, the wrap-around angle is 180° and the material is removed continuously. In the case of trochoidal milling, the material is removed sequentially with higher feed movements and lower depths of cut. During this process, the temperatures in the tool and in the workpiece are lowered; moreover, the cutting forces grow weaker. In combination with suitable cutting parameters and a tool geared to the process, a depth of cut up to two times of the tool diameter can be reached by the trochoidal milling [10, 11, 12].

3 ASSESSMENT OF THE PROCESS EFFICIENCY REGARDING ENERGY CONSUMPTION

In engineering, the efficiency of a process of a system is demonstrated by the quotient of effort and benefit. Mori [13] and Dietmair [14] set up an equation to express the energetic efficiency of a cutting process. In this equation the work brought into the cutting process W is related to the material removal rate MRR. The result is expressed in the variable Y. The smaller Y, the more energetically efficient is the cutting process.

$$\mathrm{Y} = \frac{W}{\mathrm{MRR}} \quad (1)$$

Besides the specific consumed energy Y, the energy productivity E of a process is of a higher interest for an economic consideration [15]. The economic potential in relation to the used energy can be assessed by the quotient of part costs C_{Part}, the benefit, and the amount of energy costs per part C_{Energy}, the effort.

$$\mathrm{E} = \frac{\mathrm{C_{Part}}}{\mathrm{C_{Energy}}} \quad (2)$$

In this case, the used amount of energy of the machine tool or the machine components relevant for the cutting process can be taken as a basis.

4 INTERNALLY COOLED TURNING TOOL

4.1 Experimental Setup

Machine Tool, Cutting Tool and Cooling System

All cutting trials were undertaken on the CNC turning and milling centre TRAUB TNX 65. The machine tool is equipped with an opening for measurement lines and coolant hoses. Moreover, holders that prevent the contact between the rotating main spindle and the coolant hoses were installed in the workspace.

The internally cooled tool consists of four major parts: shaft, selective laser sintered tool head, micro-cooling device and temperature sensors (figure 2). The geometry and shape of the tool was designed in accordance to DIN 4984, CSBPL 2525M. The tool holder is optimised for indexable inserts type SPUN 120108. Theses inserts are made of cemented carbide type K10. A pump and cooling system is connected with the tool holder to provide coolant at the right temperature.

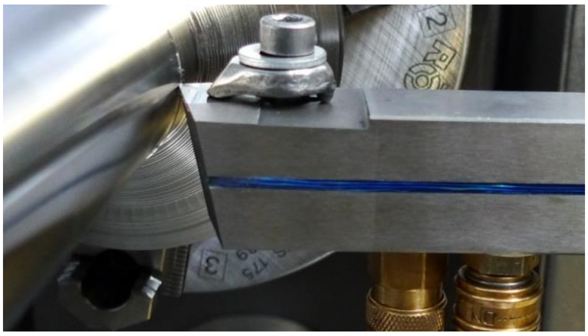


Figure 2: Side view of the internally cooled turning tool with integrated temperature sensors

Measuring Equipment

The measurement of the tool wear, especially of the crater wear, on the indexable inserts was done by a MikroCADpico by GFMESSTECHNIK. Cutting forces were measured with a KISTLER Type 9121 three-component dynamometer. The dynamometer was connected to a charge amplifiers type KISTLER 5011. In addition to this, temperatures of the coolant at the inlet and outlet of the micro-cooling device were measured by thermocouples K-type. These values were used to calculate the heat that was removed by the micro-cooling device. The thermocouples and the force measurement setup were connected to a NATIONAL INSTRUMENTS type 6251 data acquisition system. The signals were analysed and documented with LabView a NATIONAL INSTRUMENTS software.

Table 1 : Comparison of different cooling approaches for turning TiAl6V4

	Variable	Unit	DRY	DRY + ICT	WET	WET + ICT
Average Mechanical Spindle Power	P_{MECH}	W	281	290	332	343
Heat Removed by the ICT in Average	$\overline{Q}$	W	–	18	–	3
Average Cutting Force	$\overline{F}_c$	N	177	179	181	186
Relative Crater Wear in Correlation to Crater Wear under Wet Cutting Conditions	V_{CR_REL}	$\frac{mm^3}{mm^3}$	10	4.17	1	0.25
Work of the Tool Machine for Cutting 25 cm³ TiAl6V4	W	Wh	434	466	578	610
Costs per Cutting Process in Correlation to the Energy Consumption and Tool Wear	C_{ZER}	€	15.04	6.29	1.55	0.43

The measurement of the power consumption was undertaken by using the multifunctional power meter SENTRON PAC 4200 and current transformers by SIEMENS. Six current transformers were used to measure two 3-phase power lines at once.

Cutting Process

The internally cooled tool was used for all cutting trials to avoid unwanted variance by e. g. alternating cutting tool stiffness. For the turning trials the process of fine machining was chosen and TiAl6V4 was cut according to the following cutting parameters:

- Speed of cut v_c = 72 m/min
- Depth of cut a_p = 0.60 mm
- Feed f = 0.15 mm

Pre-trials showed that the lifetime criterion, crater depth of 25 µm, with these cutting parameters in dry machining is reached at a volume of removed material of 25 cm³.

4.2 Results and Discussion

The performance measurement at the TRAUB TNX 65 showed that the effective power is 5.5 ± 0.2 kW in a ready-to-operate condition. These requirements are mainly caused by the lathe's chuck hydraulics supply, by the centralized lubrication system, by the servo amplifier of the axis drives, by the cooling of hydraulic fluid, by the sensor- and path measuring systems, by the industry computer as well as by transformer, relays and switches. The last-mentioned parts are inductivities that can clearly be seen in the machine's reactive power demand as this is 2.5 ± 0.1 kW in a ready-to-operate condition. Whenever cutting trials are undertaken and the machine is switched from a ready-to-operate to an active condition, the energy consumption of the TRAUB TNX 65 increases. The increased demand is caused by the feed axis, by the main spindle, by the chip conveyor and by the cooling systems. Depending on the different cooling strategies, the machine's effective power lies between 5.8 and 7.7 kW, see Figure 3. In case of dry machining, the average effective power of the machine tool is 5.85 ± 0.05 kW. The average effective power in the case of wet machining is 7.6 ± 0.1 kW. If the internally cooled tool is used in dry or wet machining, the average effective power for cooling and provision of the coolant, tempered at 15.6 °C, increases by 0.4 kW to 6.2 or 8.1 kW respectively. The effective power of the main spindle correlates with the measured data of the force measurement. In the case of dry machining the cutting forces are the lowest with an average of $\overline{F}_c$ = 177 N, whereas they increase to $\overline{F}_c$ = 186 N in the case of wet machining in combination with the internally cooled tool, see Table 1. By cooling the cutting zone with CL the cutting temperatures are reduced.

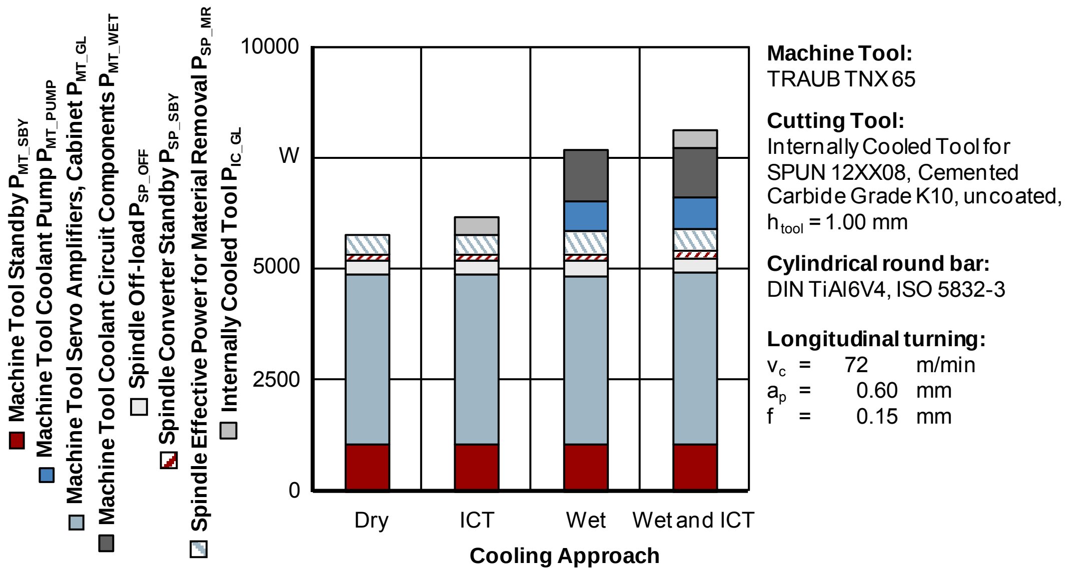


Figure 3: Effective power of the CNC turning and milling centre TRAUB TNX 65 under different cooling approaches

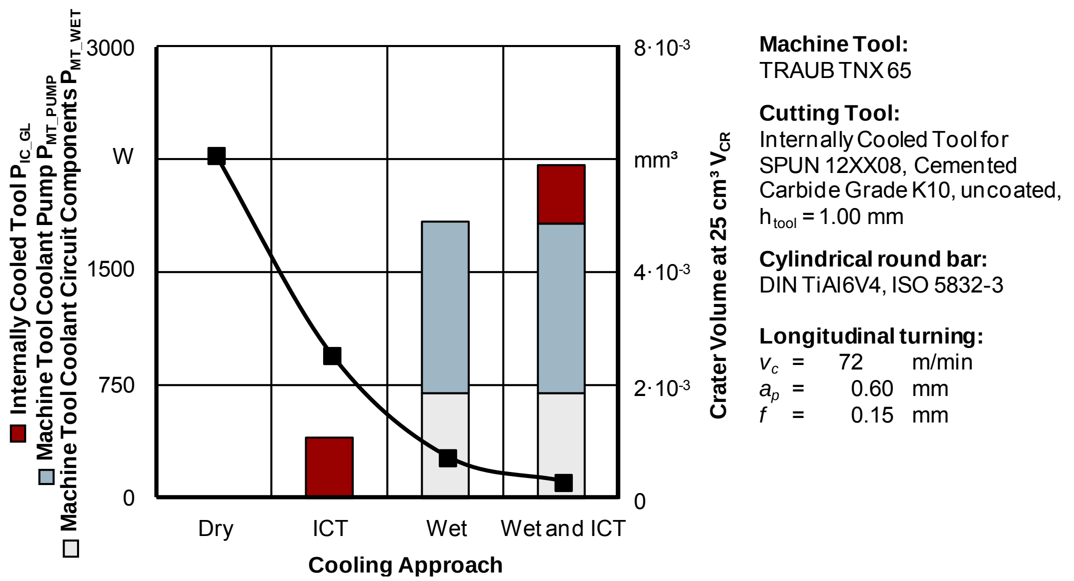


Figure 4: Comparison of the effective power under different cooling approaches and the tool wear for turning TiAl6V4

This temperature reduction is paralleled by a strengthening of the TiAl6V4 [16]. In direct comparison to dry machining the measured cutting forces of wet machining are even higher, but the friction and, thus, the cutting force can be reduced by the lubricating effect of the CL. The fact that the influence of the internally cooled tool on the cutting forces is of a different dimension in the case of dry machining and wet machining has to be emphasized. If the internal cooling system is switched on in dry machining with the internally cooled tool, an increase of the average cutting force by 2 N can be monitored.

This implies a reduction of cutting temperature and the influence of the internal cooling on the cutting process. The same effect can be seen in the case of wet machining: the average cutting force increases by approximately 5 N with a switched-on internal cooling.

The reason for this is that the released heat energy flows into the workpiece, into the chip and into the tool in the case of dry machining. Due to the missing cooling by cooling liquid, the internally cooled tool mainly works as a heat sink. The heat absorption capacity is limited to a coolant temperature of 15.6° C at the coolant inlet and at the fixed flow of the fluid. This is why the cutting temperatures cannot be further reduced by the internally cooled tool in the case of dry machining and a set average mechanical spindle power of approximately 290 W, although a thermal power of approximately 18 W was removed by the internally cooled tool. In contrast to this, an enormous part of the released heat energy is absorbed by the CL in the case of wet machining, in which the average mechanical spindle power is 332 W due to the lower cutting temperatures. If the internally cooled tool is used additionally, the absorbed heat is approximately 3 W. In the case of wet machining, the chip, the workpiece and the tool are directly cooled by the CL. The cooling of the area of heat generation, the interface between material and tool, however, is not done directly by the CL. This is as due to the high surface pressure between workpiece material and tool and the resulting tight fit no CL can get into the heat generation zone. The cutting zone is, therefore, indirectly cooled. The CL cools the going off chip, reduces its temperature and, thus, lowers the temperature of the cutting zone. The combination of wet machining and internally cooled tool leads to a two-way cooling of the cutting zone: the cutting zone is cooled by the cooled chip, on the one hand, and by the internally cooled tool, on the other hand. The advantages of the internally cooled tool in the case of dry machining become apparent in the crater wear, a typical type of wear in the case of longitudinal turning of titanium. After a volume of removed material of 25 cm³, the average crater wear in dry machining was $1.5\cdot10^{-3}$ mm³; a value that reached the tool life criterion. By switching on the internal cooling, the crater wear could be reduced to $6.1\cdot10^{-4}$ mm³. In case of a conventional wet machining an average crater volume of $1.5\cdot10^{4}$ mm³ was measured; whenever the internal cooling system was switched on in addition to the wet machining, the crater volume could be reduced by 400 % to $3.78\cdot10^{-5}$ mm³. This improvement in wear behaviour can be achieved by the use of energy intensive cooling and pumping systems; in the case of wet machining the CL pump and valves are switched on. These components lead to a permanent effective power demand of 2.3 ± 0.1 kW, no matter how much CL is needed, see Figure 4. If the wear behaviour is related to the power consumption of the machine tool, it can be seen whether the use of lubricating systems or internally cooled tools with closed cooling circuits is energetically reasonable. In order to clarify this, the equitation of energy productivity and the specific consumed energy [13, 14, 15] were combined. Thus, the variable C_{ZER} is defined. This variable contains the costs of the used electrical energy c_{Energy} and the costs of tool wear c_{Tool} for a specific cutting process. In this formula the work W of the process is multiplied with the cost for energy. For the costs of the tool the crater wear V was set in relation to the crater wear of the reference process V_{REF}. As a result of this V_{CR_REF} is the relative crater volume, see Table 1.

$$C_{ZER} = c_{Energy}W + c_{Tool}V_{CR\_REL} \qquad (3)$$

As assumption: the price for electricity is c_{Energy} = 0.09 €/kWh and the price for the indexable insert that was used in the internally cooled tool is c_{Tool} = 1.50 €/edge.

The results of this calculation can be found in Table 1. The wet machining combined with the internal cooling is producing the lowest costs with 0.43 € per 25 cm³. Whereas, the conventional wet machining process costs 1.55€ per 25 cm³ removed TiAl6V4.

5 TROCHOIDAL MILLING

5.1 Experimental Setup

Machine Tool, Cutting Tool and Cooling System

A 5-axis-machining centre, type RXP600DSH, of the company RÖDERS GMBH was used for the cutting trials. This machine tool is equipped with three linear and two rotatory axes. Like this, a 5-axes multiprocessing is possible so that it can be used for the production of single components, complex geometries and free-form components, e. g. Blisks. The spindle with a maximum speed n = 160.000 U/min is a speciality of this machine. The control system RMS6, developed for high speed cutting applications, is an in-house development of RÖDERS GMBH. An advantage of this machine is the high dynamic of its axes, the high stiffness and the positioning accuracy of 3 µm linked to it.

For the milling of TiAl6V4 a cemented carbide milling tool with a diameter of D_T = 10 mm was used. The milling tool with six cutting edges shall increase the processing of the TiAlN coating, applied by the physical vapour deposition method, significantly. The tool's maximum depth of cut is a_p = 22 mm. The cutting edges show a rounding of approximately 4 to 6 µm. A sharp edge is one requirement in the processing of high temperature-resistant material [17, 18, 19].

To cool the tool, CL is is sprayed into the cutting zone from the outside. This is done through cooling channels in the interior of the tool holder that end at the front side and spray the CL directly into the flute of the milling tool. During this process, the pressure of the CL is p = 60 bar.

Cutting Process

The reasons for the different cutting parameters of the trochoidal and the conventional milling process are found in the developing forces and temperatures. The cutting forces are higher in the case of conventional milling due to the wrap angle of 180°. Therefore, the depth of cut of 20 mm of the reference slot could only be reached by repeated cutting. The power measurement was done by the SENTRON PAC4200 of SIEMENS, as in the case of the turning trials.

5.2 Results and Discussion

The effective power measurement at the machining centre RXP600DSH of the company RÖDERS GmbH revealed an average basic power consumption of P = 5400 W in the non-operating state which is defined by aggregate that are permanently in an operating condition, see Figure 5. During the cutting trials, an enormous increase of the effective power consumption can be monitored; a fact that especially results from the moving feed axis, the rotating milling spindle, and the supply of CL. An approximate loss of power of 5 % can be observed during the conventional milling with $P_{konv.}$ = 8500 W compared to the trochoidal milling with $P_{trocho.}$ = 8900 W, see Table 2. Due to the milling tool's maximal possible feed of $a_{pkonv.}$ = 2 mm, ten cuts are necessary to reach a depth a_p = 20 mm in a conventional slot milling process. That leads to an effective cutting time t_c = 150 sec. Compared to that a cutting time t_c = 126 sec is needed to manufacture the slot by trochoidal milling, i. e. an increase of rate of material removal of 17 %. The reduction of machining time is referable to the near-net shape feed of the milling tool, $a_{ptrocho.}$ = 20 mm, that is possible due to the kinematically determined reduction of the wrap angle during the processing and the reduced cutting forces linked to it. Considering the total energy consumption, it can be determined that approximately 12 % more energy is needed for the conventional milling strategy with W = 354 Wh. This fact can be explained by the increased cutting forces compared to the trochoidal milling strategy. Moreover, in the trochoidal milling process, the cutting temperature is lowered by a reduction of the wrap angle, accompanied by higher process parameters. In addition to that and regarding the relation of work to the volume of removed material Y, Table 2 shows that the coefficient decreases by 23 % could be identified for the trochoidal milling process, compared to the conventional milling strategy.

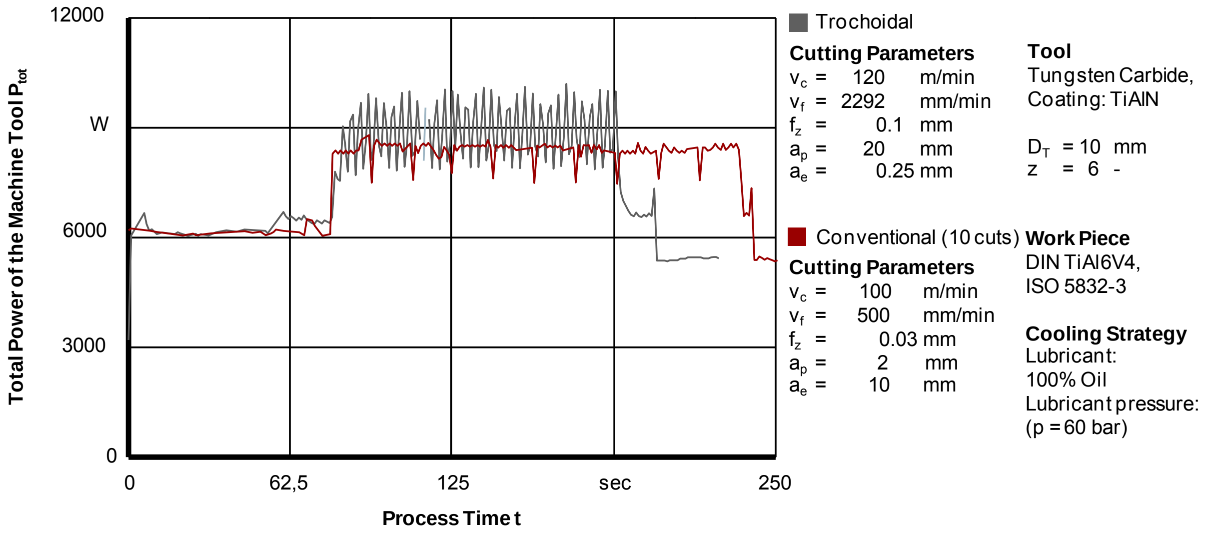


Figure 5: Effective power consumption of the machine tool when milling TiAl6V4 at different cutting strategies

Table 2: Comparison of the energy demand for manufacturing one 20 mm slot

	Conventional Cutting Process	Trochoidal Cutting Process
Work of the Tool Machine for Cutting W in Wh	354	315
Total power P_{tot} in W	8500	8900
Material removal rate Q in mm^3/sec	142.9	173.5
Y in Wh/cm^3	19.2	14.8

Finally, it has to be concluded that the trochoidal milling process enables a lower energy consumption in the processing of high temperature-resistant material due to the increased volume of removed material, although the limits of possible cutting parameters for trochoidal milling have not been reached yet.

6 SUMMARY

Two approaches for energy saving are presented in this paper for turning and milling TiAl6V4 workpieces.

The major outcome of the cutting trials with the internally cooled turning tool is that the tool wear under dry cutting conditions is in between dry and wet machining, whereas the combination of the internally cooled turning tool with wet machining leads to strongly increased tool lifetimes. In contrast to this, the energy demand under dry cutting conditions is much lower than under wet cutting conditions. With respect to the environmental protection, the best tool cooling is dry cutting combined with the internally cooled tool.

To achieve higher productivity rates or increased tool lifetimes, the combination of wet machining and the internally cooled turning tool is the best solution. In comparison to conventional milling, the average effective power consumption of the machine tool under trochoidal cutting conditions is increased by 6 %. Nevertheless, the amount of used energy is decreased by 15 % and the process time is reduced by 35 %. The reasons for this are higher material removal rates, due to the fact that the cutting time per edge and revolution can be reduced to a minimum. The heat-up phase and the cutting temperatures are small. By increasing the cutting parameters, e. g. cutting speed or feed, it is possible to improve the material removal rate. This enables a higher energy productivity and lower process time. The milling tool was used for both milling strategies. For trochoidal milling the tool has sufficient potential to increase the cutting parameters. For the conventional cutting process, however, the tool works at the load limit.

7 ACKNOWLEDGEMENT

We would like to thank the DFG for supporting the research on the internally cooled turning tool within the CRC 1026 Sustainable Manufacturing.

For their experimental work, we would like to thank Philipp Mantzke, Robert Anger and Erik Holubek. Additionally we would like to thank Sarah Fürstmann for the correction of the translation.

8 REFERENCES

[1] Bergmann, W., 2003, Werkstofftechnik, Carl Hanser Verlag, Book.

[2] Bürgel, R., 2001, Handbuch Hochtemperatur-Werkstofftechnik, 2. Aufl. Vieweg, Book.

[3] Meinecke, M., 2009, Prozessauslegung zum fünfachsigen zirkularen Schruppfräsen von Titanlegierungen, Apprimus, Dissertation.

[4] Peters, M., Leyens, C., 2002, Titan und Titanlegierungen, Wiley-Vch, Book.

[5] Rothenbücher, S., Kuhrke, B., 2010, Energiebündel auf dem Prüfstand, WB Werkstatt + Betrieb, 9: 130-137.

[6] Denkena, B. et al., 2011, Effiziente Fluidtechnik für Werkzeugmaschinen, wt Werkstattstechnik online, 101/5:347-252.

[7] Klocke, F., Eisenblatter, G., 1997, Dry Cutting, Annals of the CIRP-Manufacturing Technology, 46/2:519-526.

[8] Uhlmann, E., Fürstmann, P., 2012, Tool Wear Behaviour of Internally Cooled Tools at Different Cooling Liquid Temperatures, 10th Global Conference on Sustainable Manufacturing, Conference proceedings.

[9] Denkena, B., Hülsemeyer, L., 2012, Werkzeugmaschinen - Wege zur Energieeffizienz, Mehr Energieeffizienz!, Metallbearbeitung Werkzeugbau, Conference Proceedings.

[10] Otkur, M., Lazoglu, I., 2007, Trochoidal Milling, International Journal of Machine Tools and Manufacture, 47:9: 1324–1332

[11] Rauch, M., Duc, E., Hascoët, J.-Y., 2009, Improving Trochoidal Tool Paths Generation and Implementation Using Process Constraints Modelling, Internal Journal of Machine Tools and Manufacture, 49/5:375–383.

[12] Uhlmann, E., Fuentes, J., 2012, Innovative Bearbeitungstechnologien für hochwarmfeste Werkstoffe, FUTUR, 1:14-15.

[13] Mori, M. et.al., A Study on Energy Efficiency Improvement for Machine Tools, CIRP Annals Manufacturing Technology, 60:145-148.

[14] Dietmair, A., Verl, A., 2008, Energy Consumption and Optimization for Production Machines, ICSET Conference, 574-579.

[15] Uhlmann, E., Duchstein, B., Arnold, L., 2012, Höhere Energieproduktivität von Werkzeugmaschinen, WB Werkstatt + Betrieb, 11: 26-30.

[16] Marmy, P. et al., 2000, Tensile and fatigue properties of two titanium alloys as candidate materials for fusion reactors, Journal of Nuclear Materials, 283-287:602-606.

[17] Giessler, J., Bohnet S., 2010, Komplexe Werkstücke aus Titan effizient Zerspanen, Maschinenmarkt, 1-7.

[18] Wiemann, E., 2006, Hochleistungsfräsen von Superlegierungen, Fraunhofer IRB, Dissertation.

[19] Gerschwiler, K., 2002, Drehen und Fräsen von Nickelbasislegierungen, Perspektiven der Zerspantechnik. Entwicklung und Integration der Fertigungsprozesse von morgen, 183-197.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

18.5 Rapid Sustainable Plant Assessment (RSPA) – Experiences of practical application and its impact on the further development

J. G. Steingrímsson [1], H. Weinaug [2], N. Oertwig[3]

[1] Department of Machine Tools and Factory Management, Technische Universität Berlin, Germany

[2] Division of Corporate Management, Fraunhofer IPK, Germany

[3] Department for Quality Science, Technische Universität Berlin, Germany

Abstract

Sustainability may have the means to ensure that manufacturing can prevail at the forerun of modern societies, ensuring a profitable productivity without harming the environment and societal values. Without establishing means to evaluate how well the sustainability is carried out in the manufacturing industries, this cause is lost. The Rapid Sustainable Plant Assessment (RSPA) tool was developed in 2012, to assess how well manufacturing enterprises are doing in the different dimensions of sustainability.

This paper discusses the development that the RSPA tool has undertaken in order to increase the general applicability of the tool and the industry direction created in order to assess specific industry's characteristics. Also, primary results of industrial application are presented. The paper also provides an outlook on further development of the tool and proposes mechanisms to seamlessly integrate the RSPA results to more detailed analysis methods such as the multi-perspective modelling.

Keywords:

Plant Assessment; Rapid Sustainable Plant Assessment; Sustainable Manufacturing, Multi-perspective Modelling

1 INTRODUCTION

Sustainable manufacturing on a global scale requires a setup of plants that act as a symbiosis, an integral part of a whole where the three dimensions of sustainability: Economic, environmental and social are adequately dealt with. From an environmental point of view such setup within the earth's ecosystem would enable reuse of all outputs, regardless of if they are desired outputs such as products or if they are undesired outputs such as scrap, waste and emission. Non-renewable resources cannot be used to a greater extent than they can be recycled at and renewable resources cannot be depleted at a greater pace than they are regenerated. From a social point of view, these plants would have to benefit from its nearest surroundings as well as benefitting these same surrounding. Lastly, in order to maintain its livelihood the plant has to gain a constant profit in order to be able to flourish [1].

A manufacturing plant within such as symbiosis would be referred to as a sustainable plant and the idea behind the rapid sustainable plant assessment (RSPA) is to assess with limited accuracy how manufacturing plants are from that goal. The assessment tool was developed in 2012, where each dimension of sustainability is divided into categories and each category is then assigned with specific indicators. For each indicator there are questions assigned to it. Under the environmental dimension there are three categories: Environment, resources and energy. Under the economic dimension there are four categories: Production, quality management, product and innovation. The third and last dimension, social has four categories: Equitableness, transparency working surroundings and health. The questions are aimed at indicating how well the manufacturing plant carries its operations according to each category. The three dimensions of sustainability (environmental, economic and social) and the eleven categories remain as developed. Figure 1 shows the RSPA category break down structure [2].

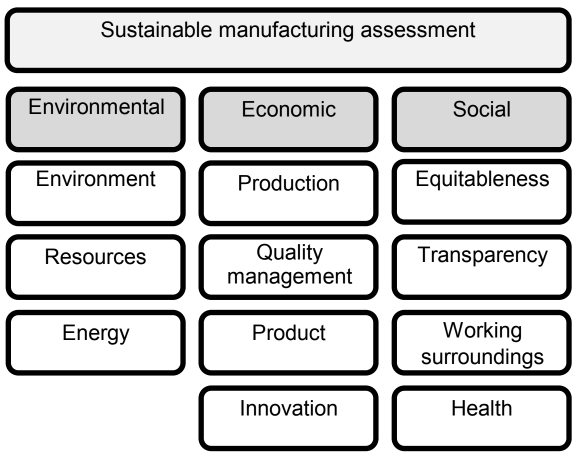


Figure 1: RSPA category break down structure [2]

When conducting the assessment, a team of judicious experts walk through a manufacturing plant, observing how the manufacturing processes are conducted. The experts observe, pose questions and evaluate operations ranging from the workshop floor, where the machine operators work, up to the management level where foremen, middle managers and mangers sit who are responsible for the

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

control and management of the plant. Each question is answered either with ‘yes’ or ‘no’ on a prepared questionnaire during the plant walk through. After conducting the assessment the team meets up and carefully deliberate the score for each indicator.

The score ranges from ‘1’ to ‘7’ where ‘1-3’ means ‘not conducive to sustainability’, which reveals a large deficiency and demonstrates the greatest potential for development. A ‘4’ describes the overall average of sustained efforts and should be understood as to ‘promote sustainability’. ‘5-6’ are above average ratings and are ‘very useful for sustainability’. They are desirable classifications, range at the top of what is possible and are consistent with sustainable production. The highest grade ‘7’ is more than a perfect score. It describes an ideal, an unprecedented state of new standards and thus to be regarded as particularly innovative. For this reason, this score will be awarded only rarely. Furthermore, such scores should be analysed further for dissemination purposes, thus improving the sustainability of the manufacturing industry.

2 INITIAL APPLICATION OF RSPA IN FOUR USE CASES

The RSPA was pretested within various types of industries before the prototypical tool was launched. These industries are amongst others automotive industry, motorcycle industry, special purpose industry, food processing industry, primary material processing industry and reconditioning industry. The RSPA pretesting yielded various enrichments to the tool and showed that it was generally applicable to be used independently of manufacturing industry type but preferred to be used by enterprises falling under the definition of small and medium enterprises (SMEs) as defined according the European Union, which make up 99% of the European industry [3]. Manufacturing industry is based on the classification offered by the International Standard Industrial Classification of All Economic Activities under section C – Manufacturing [4].

The following sections describe the initial prototypical use cases of the RSPA tool.

2.1 Use cases’ description

The RSPA was applied the first time under real conditions and in several enterprises. The initial aims of the RSPA were:

- To gain experiences in the use of the instrument RSPA under real conditions.
- To measure if the required real time to completely perform the RSPA evaluation per enterprise fits into the two hour objective.
- To check the applicability of the used questions, their relations and clustering.
- To get experiences in the handling of the rating scale and evaluation scheme.
- To get a feedback from the evaluated enterprises regarding the quality and impact of RSPA results.
- To gain a valid base the enhance the RSPA

For this first real-case application of the RSPA, an initial prototypical version was used. This version consists of an MS Excel-based questionnaire and evaluation sheet with semi-automatic calculation of the evaluation profile.

The test itself has been performed in the context of a Russian-German energy und resource efficiency project supported by the German Ministry of Education and Research [5]. This project is intended to strengthen the competitive position of Russian enterprises by stimulating environmental behaviour and acting supported with practically applicable solutions for increasing their material efficiency and productivity with reduced energy consumption [6].

Four enterprises in the Russian Samara region have been investigated. Hence, the use case took place under specific Russian economic and social condition. These conditions are characterised by closed energy market due to state-owned energy supplier and the Russian law with its implementation in the area of waste treatment, occupational health and safety. All enterprises selected for the RSPA case were automotive supplier but from very different industrial sectors. They produce casted aluminium components for gears, motors and pumps, die cut and punched sheet metal parts, moulded plastic panelling, vibration-damping and noise absorbing products. With 25 to 125 employees the enterprises are small and medium-sized enterprises and fit in the application scheme for RSPA.

The RSPA tool was applied as an expert survey at all four enterprises. In addition, the results were discussed with two enterprises, whereas the evaluated indicator values were adapted partially due to inadequate access to the management level at the time when the RSPA was conducted. Table 1 summarizes the performed RSPA activities related to the enterprises and their industrial sector.

Enterprises’ industrial sector	RSPA expert survey	RSPA-results evaluated by the enterprise
Vibration-damping and noise absorbing products	✓	✓
Metal treatment (die cutting and punching)	✓	✓
Aluminium casting and mechanical treatment	✓	Planed
Plastic injection moulding products	✓	Planed

Table 1: Performed application cases

2.2 Results, experiences and lessons learnt

For the case of acquiring comparative results from the surveys, a single expert conducted the assessment. That particular expert had already gained knowledge into the plant’s interiors through the collaboration with the enterprises through the energy efficiency project as well the by special observation of the enterprises’ shop floor and premises.

The evaluation results are summarized in Figure 2, which shows the RSPA evaluation profiles of the four enterprises regarding to the individual sustainability’s categories. It shows that from the 44 evaluated categories (each point on the graph is an evaluated category score), only 15 categories were rewarded with score higher than 4 and no score was higher than 5. These results clearly indicate that there is an arduous task at the hands of these enterprises, however, investigation on the individual indicators of each category revealed where direct action could be taken.

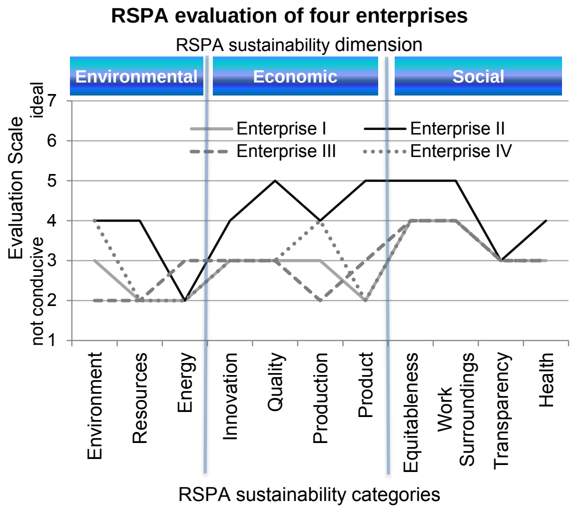


Figure 2: RSPA evaluation profile of four enterprises

This proved to be of importance to the enterprises being assessed, especially since the improvement potentials identified were generated in an easily understandable manner, within a very short timeframe. Furthermore, the application tests were very successful and delivered the evidence that the RSPA is:

- A smart approach to systematically grasp an initial set of enterprise information.
- That are grouped and evaluated regarding sustainability categories and dimensions.
- Delivers a perfect base to fast identify action potentials.
- Start a deeper discussion with the enterprise.

For example, at the enterprise II (Figure 2) a gap in energy efficiency has been identified. A look into the detailed questions and statements of the RSPA energy category discloses as reasons a) old and energetic inefficient equipment, b) nearly no building insulation and c) no energy monitoring and management system. Another critical area is transparency, especially due to missing direct commitment towards sustainability and related documentation. Nevertheless, partially indicators are calculated but used only at management level. For other enterprises the RSPA indicates the resource efficiency, product or production as categories with the largest improvement potential, whereas the related reasons differ dramatically between the enterprises. The application of the RSPA itself could be performed relatively smooth, but the required time lasted more than the aimed two hours. In some cases the two hours were completely necessary to fill out the RSPA table, but not available for the visiting of shop floor or enterprise. For sure some time was lost because of the first application and therefore missing experiences in RSPA of the expert. But this can be reduced in the future by creating an application guideline for the expert that for example explains:

- The use of the evaluation scale with practical examples.
- The locations to be investigated (e.g. shop floor along the material flow, socially used rooms as cantina and rest/recreational rooms).
- A list of potential interview partners (roles).

Additionally, a short introductive presentation for the interview partners briefly describing the objective and method of RSPA could both motivate the interviewee and reduce the required time. As final point to reduce the RSPA application time, the testing expert suggests to revise the questionnaire into the direction of a more streamlined set of questions and the concentration of the most important facts.

As already explained the test took place at Russian enterprises. The fact that the initial RSPA questionnaire was available only in German language, but was applied together with Russian partners and an English-Russian Interpreter, led to some challenges in translating specific terms and discussions with the interviewees. These terms and questions mostly came from the social dimension and have cultural or legal backgrounds, e.g. flexible working time, employee participation (labour union) or financial precautions (pension). Hence, future version of the RSPA should be multi-lingual to guarantee the right interpretation of the questions and the comparability of the results.

As original idea the RSPA was planned as instrument for a pure expert's evaluation. However, the application within the test went beyond this approach and performed the expert's evaluation followed by a detailed discussion of the evaluation results with the assessed enterprise (Table 1). This procedure gained a lot of interesting experiences. Figure 3 compares the RSPA evaluation profiles of one exemplary enterprise based on the expert's evaluation and the revised version after the discussion. The discussion with the enterprise attests the general applicability of the RSPA questionnaire and the related evaluation. Nevertheless, it interestingly delivered many new details and unknown facts not recognized during the expert's evaluation, which led to a slight adaptation of the evaluation based on specific traceable reasons. The evaluation results were adapted in a better direction (i.e. categories product and work surroundings) but also to a worse direction (i.e. environment). Summarizing, the discussion led to more details and – more importantly – to a common and agreeable understanding of the argumentation and evaluation. This was an ideal base for the next step to commonly develop an action plan related to improve the identified potentials.

Even though that the adaptation of the evaluated values has shown an effect as shown on the top side of Figure 3, the RSPA calculation of the sustainability dimensions on the bottom side of Figure 3 did not changed although the evaluation values of the categories were different. This low sensibility of the dimension calculation combined with the tendency to round down the value indicates that there could be a tendency towards lethargy or demotivation towards the sustainability objective.

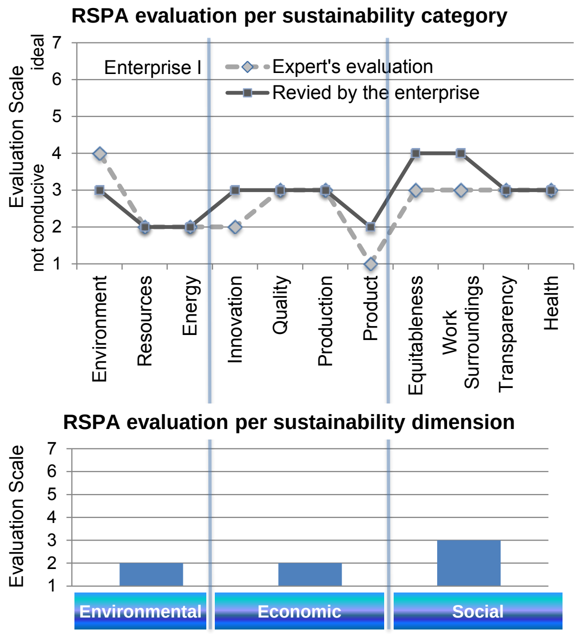


Figure 3: Evaluation profiles of one enterprise before and after discussion with the enterprise

Further specific feedbacks from the application test mostly related to specific questions which should be taken into account within a revised RSPA version:

- Specification of a more detailed evaluation scale and reference value. Examples would be good to reference the best practice by region such as Brazil, Russia, India and China (BRIC) countries, Western Europe, Eastern Europe, North-America, South-America and Africa. Such bespoken adjustment could propel sustainability development within the specific regions.
- Specification of a way to handle or deactivate non-relevant evaluation questions. This refers to questions that are not required in some instances such as request of treatment installation where no hazardous materials are used within the manufacturing process.
- Incorporation of enterprise size specific and industry specific questions. A large automotive plant has different requirements than a ready-made meals packaging line.
- Elimination of misleading or double negative questions to ensure that the clearest picture of the plant's sustainability score is obtained.
- Ensure the unified questioning scheme and use of the evaluation scale (e.g. avoid that once is asking for 'No emission certificate' with 'Yes'/'No' answering possibility followed with 'Useful transport conception' with 'Yes'/'No' answering possibility.
- Ensure that the dependencies between the different questions are marked clearer. An example would be where hazardous materials are used in manufacturing process then there should be some kind of an indication towards the working surroundings category.

3 IMPACT TO THE RSPA ENHANCEMENT

3.1 Further development and adaptation of RSPA

The tool was relatively sensitive towards enterprise's spatial dimension and expertise of the experts conducting the assessment. As a result and in order to compensate the lack of time, some teams would have to divide tasks and assess different sections of the plant in smaller teams than initially intended. Smaller team sizes would also amplitude the lack of expertise if the team's composition would be based on specialisation in different fields.

Further development of the RSPA tool has been in place since the results from the enterprise evaluation came forward. The RSPA has 43 indicators or on average around 4 per category but they are not equally distributed. One category (innovation) has only two indicators where as another (environment) has six. To level this difference, that is to increase the number of indicators to a common number for each category is considered to be of some importance but not vital for the functionality of the tool, as in the end the average of the indicators builds the category score. Current work on questionnaire has mainly been focused on increasing clarity of the questions and to create bespoke adjustments to the RSPA tool, in order to make it more industry specific. The RSPA now has a core questionnaire that is applicable to all industry sectors and periphery questionnaire or module questionnaires that are used where required. An example would be module questionnaire on noise that is used in a very noisy environment in order to establish the plant's management determination to ensure that employees and neighbouring locations do not suffer from the noise pollution. Typical use would be for enterprises that have hearing protector requirements but only a proportion of the plant's operators is wearing them, this could be the result of enforcement problems or that hearing protectors are not selected correctly. Finding where the problem is rooted would be of great importance to the enterprise.

Other improvements made to the RSPA are towards usability and openness of the tool, thus greatly augmenting the dissemination chances of it. These improvements will be achieved by launching the RSPA tool over the internet. This internet application will require login for users, where basic contact details are required and registration for each plant visit in order to preselect the adequate module questionnaires.

Usability is specified as the ease of learning for novice users (learnability), steady state performance for expert users (efficiency), ease of using system intermittently for casual users (memorability), error rate for minor and catastrophic errors (errors) and how pleasant the system is to use (subjective satisfaction) [7]. Special focus is on the learnability aspect and trying to increase the self-explaining properties of the questions. This will be achieved by building a user's manual that increases the standardisation of the tool as well reduces the entry barrier for using the RSPA tool for evaluation.

Openness "relates to the easing of restrictions on the use, development, and commercialization of a technology" [8]. Therefore, the openness of an enterprise can be seen as the efforts an enterprise undertakes in order to enable use, development, and commercialization of a technology. Reluctance seems to be a barrier to openness, especially when it comes to getting workers to speak their mind. This aspect is great important to the social dimension assessment within the RSPA and there has to be a clear understanding that those being questioned during the RSPA, can answer without the fear of the consequences. There are indications that the Japanese manufacturing industry has reached a nationwide participative openness, where the capacity to continually challenge one's own thinking is deeply embedded in the culture as seen with lean management tools such as kaizen (continuous improvement tools) that have a widespread use in the Japanese manufacturing industry [9].

3.2 Seamless information integration between RSPA and Multi-perspective Modelling

As already stated, the RSPA aims to deliver a very first set of information regarding the investigated enterprise which is clustered and evaluated along a sustainability manner. As an initial step towards more sustainable manufacturing, the RSPA is a valuable tool due to its results, which are obtainable in a low costly and quick manner. Nevertheless, it is only the first step in longer sequence of activities leading at the end to a sustainable-operating enterprise and value creation network for generations of people. For example, the identified improvement potentials need to be transferred into improvement actions. And these are usually strongly related to the material flow along manufacturing equipment controlled by *enterprise processes* from strategic management like 'quality management' and 'budgeting' as well as by operational management processes such as 'acquisition', 'order processing', 'manufacturing planning and execution' or 'maintenance'.

The *Multi-perspective Modelling* aims to support the planning engineer with an instrument for setting-up or redesign enterprise processes to fulfil sustainability goals [10]. This new modelling method will enable understandable, operational views ('perspectives') on the enterprise processes along the value creation. The goal is to allow stakeholders to make decisions towards the sustainability in their context [11]. In this sense, the Multi-perspective Modelling acts in a more detailed information level than the RSPA, but require its information as input in two different ways:

- usage of the RSPA to identify primary the fields of action for the detailed analyses and optimization by Multi-perspective Modelling
- create a further information layer to integrate RSPA data directly into the enterprise model

The analysis and optimization of enterprise processes regarding sustainable manufacturing is a very useful, but depending on the size of an enterprise and the product complexity, also a time- and resource consuming instrument. To minimize the needed effort and to maximize the success of achieving the objective sustainability, it is essential to identify the key action areas of the analysis in the first step. The RSPA as a quick and low costly solution for a first assessment of an enterprise concerning sustainability has been found as a good starting point also for determining the complex of tasks within the modelling manner. With a first assessment via the RSPA tool the enterprise will be in a position to work well-aimed and more efficiently on processes and their transformation. Thus, the combination of both approaches will ensure that the observed weak points are mainly focussed and the needed 'perspectives' are equivalent available in the instruments of the *Multi-perspective Modelling*.

The authors also propose to transfer the gained valuable RSPA information into the Multi-perspective enterprise model. The information stored at the RSPA's database can be converted for comparative purposes, thus showing how the enterprise improves in terms of sustainability. Furthermore, by incorporating an additional information layer into the enterprise model, more functionality is achieved and the tool becomes more useful for those enterprises which are interested in becoming more sustainable. This integration layer can be named 'sustainability performance structure'. The main objective of the layer is the thematic clustering of enterprise model content in a topic-specific manner. Combined with the capability to link and assign indicator values and impact categories to model content, this would enable the (semi-) automatically evaluation of enterprise models.

The RSPA provides an evaluation scheme and certain indicators that are used for expert's assessment, clustered in sustainability categories and dimensions. The task for the future is to integrate this information in the sustainability performance structure. Hereby, the RSPA indicators are linked through the sustainability performance structure to sub-processes within the enterprise model which are influenced by them or vice versa. For example the RSPA question of the 'existence of maintenance schedules on machines' could be one entry in the sustainability performance structure under 'maintenance' in the category 'production'. Each entry includes the evaluation value but can be enriched by further information. The entries are linked to the enterprise model class 'machine' and the enterprise process 'maintenance'.

During the further planning and implementation progress the initial evaluation from RSPA attached to the enterprise processes can be refined by measured sustainability indicators. The expert's meaning of the success of a certain enterprise process is than proved by real evidences.

4 SUMMARY AND FUTURE WORK

The RSPA is an integrated and efficient instrument to quickly quantify the complex topic of sustainability with an enterprise perspective. The expert or a consultant gets a tool that delivers a first impression of the enterprises' sustainability characteristic in a structured and relatively understandable manner. The tool shows where improvement has to be carried out but cannot be used to show quantifiable results.

This paper presented lessons learnt with the initial version of the RPSA in four Russian enterprises. This test delivered a founded feedback to various aspects that the enterprises have taken to consideration. The RSPA questionnaire has been developed in terms of specialisation to different types of industries and to increase the accuracy of it through improvements to the contents of the questionnaire and the manner of how they questions are formulated. An internet based version of the RSPA is under development that will highly increase the usability and accessibility of it. The improved usability opens up the possibility that people with novice production knowledge can carry out the RSPA without dramatic decrease in the tools applicability. The increased openness makes user more involved in the improvement of it, as if they notice that there is a need for adjustment, they can propose new questions and new relations between questions in order to make the tool more aiding for other users.

Furthermore, work on the conceptual integration of RSPA with methods that go beyond the initial investigation is currently undergoing. These instruments - such as the Live Cycle Sustainability Assessment (LCSA) and the Multi-perspective Modelling - will drag the information from the RSPA which therefore become the base for a more detailed evaluation, planning and restructuring of all aspects of enterprises' sustainability.

5 ACKNOWLEDGMENTS

We extend our sincere thanks to all who contributed to preparing this paper. Especially, we thank the German Federal Ministry of Education and Research for the funding of the project "Energy und resource efficiency for Russian SME" (support code 01DJ12086) as well as the German Research Foundation DFG for the funding of the Collaborative Research Centre 1026 "Sustainable Manufacturing – shaping global value creation" (SFB 1026/1 2012). The responsibility for the content of this publication lies with the author.

6 REFERENCES

[1] Seliger, G., 2007, Sustainability in Manufacturing. Springer Verlag Berlin Heidelberg, Berlin.

[2] Steingrímsson, J.G., Heyer, S., Seliger, G., 2012, Rapid Sustainable Plant Assessment. In: Seliger, G., Kilic, S. E. (eds.) Towards Implementing Sustainable Manufacturing. Conference proceeding 10th Global conference on sustainable manufacturing GCSM, Istanbul 31.10.-02.11.2012, pp. 588-593.

[3] European Commission, 2005, The new SME definition - User guide and model declaration, Brussels.

[4] United Nations, 2008, International Standard Industrial Classification of All Economic Activities (ISIC), Rev.4, New York.

[5] Reggelin, T., Weinaug, H., 2012, Referenzmodell Energie- und Materialeffizienz bei russischen KMU, UFORDAT – Umweltforschungsdatenbank, internet database for environmental science: http://doku.uba.de [Accessed on the 16th of April 2013].

[6] Kolomiichuk, S., Trojahn, S., Reggelin, T., Weinaug, H., 2013, Analyse und Verbesserung der Energieeffizienz produzierender KMU am Beispiel von vier russischen KMU, conference proceeding X. International applied science conference on Sustainable development and effective resource policy, German-Kazakh University, Almaty.

[7] Nielsen, J., 1993, Usability Engineering. Morgan Kaufmann Publishers, San Diego.

[8] Boudreau, K., 2010, Open Platform Strategies and Innovation: Granting Access vs. Devolving Control. In: Management Science, Vol. 56, No. 10, pp. 1849-1872.

[9] Colenso, M., Patrick, C., 1999, Kaizen Strategies for Improving Team Performance, Financial Times Prentice Hall, Harlow.

[10] Jochem, R., Weinaug, H., Schäfer, M., 2012, Requirements, potentials and constraints of a semantic approach to model and access the sustainability within business processes, In: Seliger, G., Kilic, S. E. (eds.) Towards Implementing Sustainable Manufacturing. Conference proceeding 10th Global conference on sustainable manufacturing GCSM, Istanbul 31.10.-02.11.2012, pp. 435-440.

[11] Rabe, M.; Jochem, R.; Weinaug, H., 2011 Multi-perspective Modelling of Sustainability Aspects within the Industrial Environment and their Implication on the Simulation Technique, In: Seliger, G.; Marwan, K. K.; Jawahir, I.S. (Eds.) Advances in Sustainable Manufacturing. Springer Verlag, pp. 313-318.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

18.6 Evaluation of energy and resource efficiency supported by enterprise modeling – experiences from application cases and their significance for the multi-perspective modeling approach

R. Jochem [1], H. Weinaug [2], S. Kolomiichuk [3], N. Oertwig [1]

[1] Department for Quality Science, Technische Universität Berlin, Germany

[2] Division of Corporate Management, Fraunhofer IPK, Germany

[3] Division Logistics and Factory Systems, Fraunhofer IFF, Germany

Abstract

The multi-perspective modeling method is an enhancement of enterprise modeling and will enable understandable, operational views ("perspectives") on sustainable value creation. The goal is to allow all stakeholders to make decisions towards the sustainability in their context, ranging from individual enterprise decisions up to cooperation strategies. As known, the sustainability is based on the environmental, economic and social dimensions. The energy and resource efficiency is an essential subset within the sustainability context that affects mainly the first two dimensions. This paper presents an enterprise modeling driven and supported analysis of energy and resource efficiency, which was performed at several small and medium sized enterprises. The experiences gained from this application case are described and their consequences for the multi-perspective modeling method are argued.

Keywords:

Multi-perspective Modeling, Enterprise Modeling, Business Process Modeling, Sustainable Manufacturing

1 MOTIVATION

Day by day hundreds of operations are performed in each company either to produce something or to control the manufacturing and to fulfill all the managerial tasks, which are the prerequisite for the manufacturing and economic success of the company. Usually, the most of those activities consume more or less energy (e.g. electricity, thermal energy for heating or cooling), several use raw materials or commodities to create new products, but often generate also waste and emissions.

Methods for business process modeling (BPM) are an appropriate way to effectively describe such sequences of activities and their relations to e.g. information, equipment and personal resources, products etc. By using the BPM it is possible to model the physical material flow correlated to products proceeded through the shop floor as well as all the orders and information that are controlling the physical material flow. These information are usually the result of strategic management processes like "determine strategy", "quality management" and "budgeting" as well as operational management processes such as "marketing, acquisition", "order processing", "manufacturing planning and execution", "accounting", "maintenance" and so on. This description can be done on different levels of detail from workplace over the enterprises level up to the value creation network.

This is the reason why we talk about the *enterprise model* as result of the modeling process.

But the enterprise modeling still pushes the envelope if it is requested to describe and evaluate energy and resource efficiency. For example the systematically embedding and allocation of indicator values to certain elements within the enterprise model is still insufficiently solved. Moreover, the description of reasons why something happens, how strong this reason influences which processes and why it is in the linked sequence of actions (cause-impact-relations) requires a strengthening. For example, it could be of interest which implications to certain enterprise processes has causing on the strategically management decision to invest into energy efficiency. This of course limits the use of enterprise models in the context of designing enterprise processes leading to energy and resource efficient acting especially due to its constrained evaluation capability.

This paper describes the application cases of energy and resource efficiency analyses at several companies driven and supported by enterprise modeling (chapter 2). The findings, lessons learnt and acquired company data such as models, indicators etc. are discussed and will directly influence the development of the method of *multi-perspective modeling* within the Collaborative Research Centre SFB 1026 - "Shaping Global Manufacturing Sustainable Value Creation" (chapter 3). This will be one step forward to develop a consistent toolbox for a rapid and enterprise model-based sustainability analysis. An investigation of existing approaches to handle energy and resource efficiency supported by models shell support this development (chapter 4).

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

2 THE APPLICATION CASE - OBJECTIVE AND OVERVIEW

The application case has been performed in the context of a Russian-German energy and resource efficiency project supported by the German Ministry of Education and Research [1]. This project specifically aims to strengthen the competitive position of Russian enterprises by stimulating environmental behavior and acting supported with practically applicable solutions for increasing their material efficiency and productivity with reduced energy consume [2].

Four companies in the Russian Samara region have been investigated. Hence, the application case took place under specific Russian economic and social condition, such as a closed energy market due to state-owned energy supplier or the Russian law and its implementation in the area of waste treatment or occupational health and safety. All enterprises are automotive supplier but from very different industrial sectors. They produce casted aluminum components for gear, motor and pumps, die cut and punched sheet metal parts, molded plastic paneling or vibro-damping and noise absorbing products. With 25 to 125 employees the companies are small and medium-sized enterprises.

In the analysis phase several appointments at the site of the participating SMEs have been taken place. During this time, the enterprise processes were modeled and analyzed as well as required data on production, transportation and auxiliary processes. For each company, the energy and resources relevant production processes were modeled in detail by the method of integrated enterprise modeling (IEM) [3] in the tool MO^{2}GO [4,5]. Based on the enterprise process model, all energy and material consumptions have been recorded along the production processes.

In addition, information and data on building insulation, lighting, heating, office equipment and operation, etc. were collected. All this information led into energy flow models based on the energy value stream method [6].

An example for the relation between enterprise processes and energy flow model is shown in Figure 1. With the help of these models and the energy efficiency indicators, the participating companies were evaluated in terms of their energy and material efficiency. Subsequently, the largest energy consumer (sub-processes and individual process participants) were identified and the potential savings were calculated. These data were the basis for the determination of individual actions for energy and material efficiency gains in the participating companies.

In parallel two additional evaluations were performed. The Rapid Sustainability Plant Assessment (RSPA) is a questionnaire-based evaluation of an enterprise performed by experts. The aim is to get in limited time a rapid assessment of the enterprise's conditions in economic, environmental and social area. On the one hand, the RSPA goes beyond the scope of energy and material efficiency, on the other hand it provides usable and structured results in a very early stage of the analysis, even if there are still no well-grounded or measured values available. A basic Life Cycle Assessment analysis (LCA) has been performed at one company to get an impression how the data gained in the energy and material efficiency analysis can be applied for further purposes. For example it has been calculate the impact of the energy consume to the climate change (in CO_2-equivalence) or the impact-category terrestrial acidification (SO_2) based on the material usage of the company.

An overview about the involved companies and the performed analysis can be found in table 1.

Table 1: Performed application cases and related analysis

Enterprise	Enterprise Model		Energy flow analysis	RSPA	LCA
	Management	Production processes			
I	✓ strategic and operational processes	Vibro-damping line Noise absorbing products line	✓	✓	✓ (basic)
II	✓	Metal treatment (die cutting and punching)	✓	✓	-
III	✓	Aluminum casting Mechanical treatment	✓	✓	-
IV	-	Plastic injection molding products	✓ (basic)	✓	-

3 EXPERIENCES FROM THE APPLICATION CASE AND THEIR IMPACT ON THE MULTI-PERSPECTIVE MODELING APPROACH

The Multi-perspective Modeling Approach aims to support the planning engineer with an instrument for setting-up or redesign enterprise processes to fulfill sustainability goals [7]. This new modeling method will enable understandable, operational views ("perspectives") on the enterprise processes along the value creation. The goal is to allow stakeholders to make decisions towards the sustainability in their context [8].

During the investigation an enterprise model based on the existing method IEM has been created. The approach of a combination with several other methods used to evaluate the sustainability status of an enterprise has been used to extract several requirements for the multi-perspective modeling approach. These requirements can be structured into the four fields: data acquisition and enterprise process modeling, data processing and calculation, analysis, and visualization of the analysis' results.

Data acquisition and process enterprise modeling

Different activities were performed in this filed: a) enterprise modeling with interview partners starting from a model template, b) collection of basic company information with RSPA and general questionnaire, and c) the detailed collection of indicator values for different periods over the year, such as monthly amount over one year of electricity and heating energy consumption, water, production volume etc.

As expected, the data recording in the participating Russian SMEs turns out to be very difficult and time consuming. Often, necessary data and information were not available or are not electronically accessible, which increases the effort of data acquisition and processing. Also the kind of available data was different between each company. For example partially only the total electricity consumption for the complete company was available, another company provided it for a certain building, or values were given for a certain number of the equipment set but not for all. As consequence the data collection templates should support flexible ways to insert indicator values. For example it could contain the following four alternative options to enter the electricity consumption:

- measured electricity consumption - based on real measurement and related to a certain process and equipment
- demand of electric power * work time (for each activity)
- gaining the consumed energy for a certain area of the production e.g. value from the electricity meter of a shop floor or from the bill of the power supplier and support the calculation of the share of the consumption per process
- subjective evaluation by an expert (if no other data are available; e.g. RSPA over scale quantifiable)

Also an automatic consistency check and the check on missing data could ease the data collection.

A further challenge was the coordination between the different types of data collection because a) separate tools and instruments were used during the collection e.g. Word files, Excel tables, enterprise models, etc. and b) the collection templates were too general and non-adjusted to the available data from already performed collections. As exemplary effect the processes and equipment from the enterprise modeling were not reflected in the energy consumption collection template. But the use of templates was fruitful in general, especially the tabular collection of the large amount of detail data. Only, the transfer of the data back to the enterprise processes was missing. As consequence, the multi-perspective modeling should be able to provide easy-to-use data collection templates. These should be integrated in the enterprise model and dynamically adapted to the model content (or later vice versa adapt the enterprise model to content filled in the template).

A comparable situation appeared during the application of the Rapid Plant Sustainability Assessment. It was very useful to gain in the beginning of the assessment a structured set of basic company data and expert's evaluation. In this sense, the multi-perspective modeling acts on a more detailed information level than the RSPA, but requires its information as input. Nevertheless, the seamlessly further use of the data - for example in the enterprise model - was still insufficient. The integration of the collected RSPA indicators and information into the multi-perspective modeling is therefore one consequence from the experiences of the application case. This requires a mechanism to assign indicator values to certain elements within the enterprise model.

One potential approach to tackle the current constraints is the implementation of an additional information layer into the enterprise model. This information layer can be named "sustainability performance structure". The main objective of this layer is the thematically clustering of enterprise model content in a topic-specific manner. Combined with the capability to link and assign indicator values and impact categories to the model content, this would enable the (semi-)automatic evaluation of enterprise models.

Another effect happened through the different requested levels of data details. For example, in the enterprise model the products are described with generic names like "plastic mat". But for a more detailed analysis - like for the LCA - the very exact specification of the material inclusive the specific weight is necessary to get an LCA-value. Instead of "plastic mat" the correct kind of plastic material like polyethylene or polyurethane is requested. This becomes much more challenging if we talk about composite material like metal-laminated foil. On the other side the enterprise model contains information like organizational or IT-related issues which are not of interest for the traditional LCA or energy flow analysis. As prerequisite for the integration of the data these different levels of details need to be aligned. But the result will open new options for the evaluation.

Data processing and calculation

In the application case the calculation of indicators and visualization are logically linked to the enterprise processes but made in separate Excel sheets and tools (e.g. to draw the sankey diagram for the energy distribution or GaBi for the LCA).

The data processing within the enterprise model would enable the calculation of indicators and visualization in relation to the enterprise processes. This would increase the data consistency, reduce double work in the data collection or due to data transfer and finally offer new evaluation capabilities. However, it is not reasonable to integrate all information. For example requires the calculation of LCA impact categories and areas of protections detailed background knowledge and the access to large databases. Eventually, here the establishing of an information exchange interface has more advantages.

Analysis

The link between enterprises processes and efficiency parameters is essential. Figure 1 shows exemplary that the managerial processes in the office of one application case company require 28% of the total consumption. This is more electricity than the manufacturing in the noise absorbing products workshop. Hence, in the performing of the managerial processes itself lays a very high saving potential. It is important to recognize this direct impact of managerial processes on efficiency. To know where and which activities consume how much energy is the base to react on it. More important is the indirect impact on efficiency due to the fact that some management processes influence decisions, e.g. on investments in less-energy consuming equipment and machines. The combination of enterprises processes with efficiency evaluation methods enables the analysis for example of the impact of a changed production strategy to the energy efficiency. Moreover, the affected processes, equipment and staff can be identified.

The applied methods of energy distribution and energy flow were very useful to recognize the process and equipment with the highest consume and therefore also high improvement potentials. For example, the vibro-damping workshop was identified with 50% as field with the highest electricity consumption (figure 1). A detailed investigation of the workshop's manufacturing processes with the energy

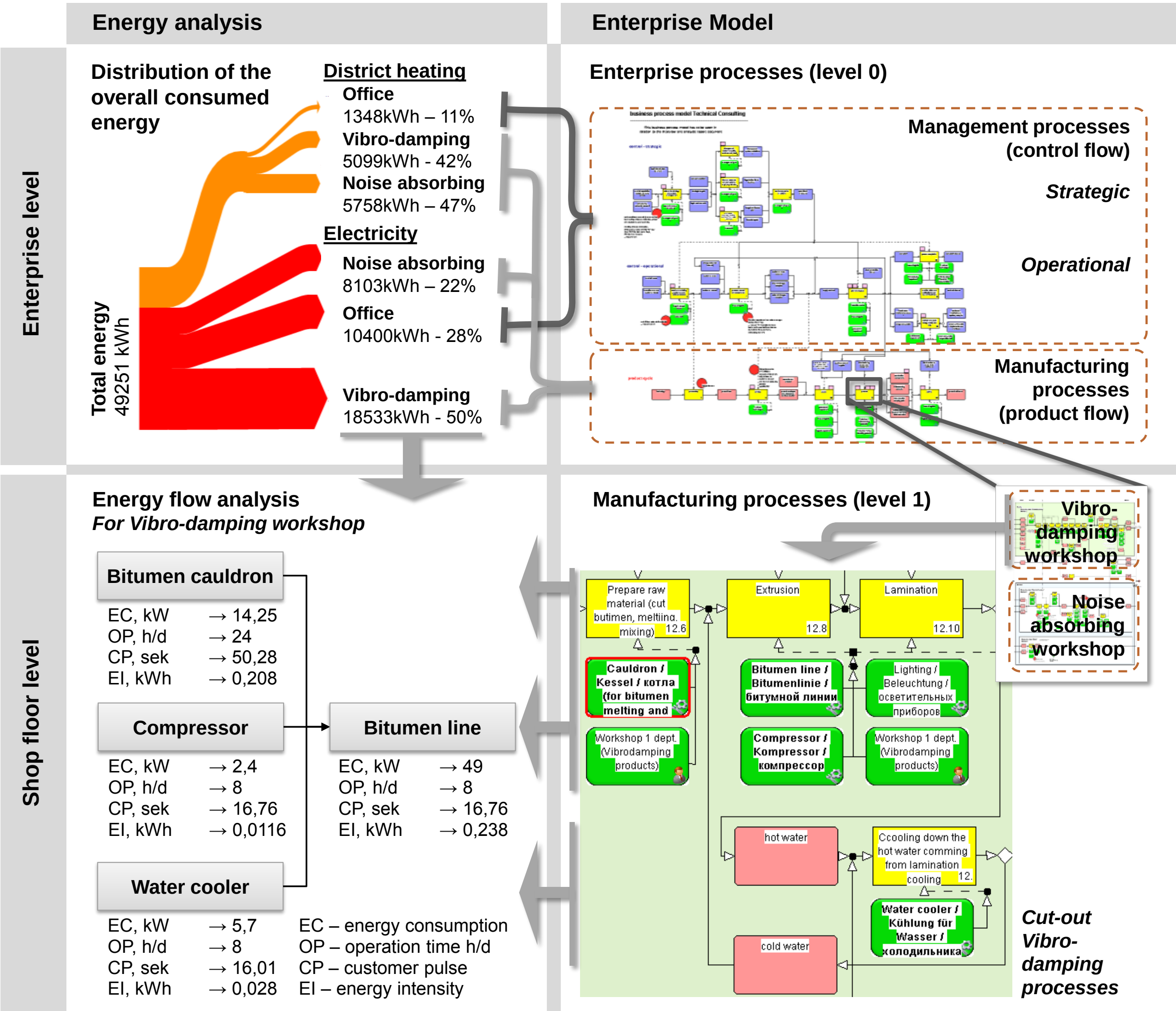


Figure 1: Relation of enterprise models and specific energy and resource efficiency analyses

flow method shows that the bitumen cauldron has the highest energy intensity within the bitumen line. The adaptation of the cauldron insolation was identified as technological improvement action that would lead into a 10% reduced energy consumption. In addition managerial improvements where identified in the enterprise model. The cauldron runs 24h (because of the danger of harden bitumen) but the working time is currently only 8h. The introduction of a shift plan could reduce the energy intensity dramatically because of lower idle periods and the switch-off of the empty cauldron. But this procedure of course affects other management issues like employment system and work plan.

Another example is the very high and over the year fluctuating water consumption identified in one company. Only 1% of the water was used for manufacturing and 99% for watering lawn and office tasks. In a further case, the identification of the missing thermostats and insulation of heating installations led to the suggestions: a) establishing of the missing equipment plus b) management instructions to the staff for energy efficient behavior (e.g. not to open the window if the heating is running). Both actions combined could save 25% heating cost with low investment and an amortization in 3,4 years. In this context the multi-perspective modeling is requested to support the design of alternative model scenarios that can be compared to each other.

Visualization of the analysis' results

The graphical visualization of the results e.g. in form of energy or material flow diagram (figure 1) was an effective way to easily find the largest consumers and therefore the area with a potentially high improvement as well as to create awareness in the analyzed companies on the field of acting. The integration into the enterprise model could offer new analytic views to the model content. Exemplary, the multi-perspective modeling could support following views (perspectives) (figure 2):

- enterprise processes combined with material flow, energy flow, value stream, the Intellectual Capital Structure (ICS) and individual Key Performance Indicators (KPI)
- marking or highlighting of direct energy or resource-intensive processes or equipment (e.g. with color-code or size or design of a graphic element)

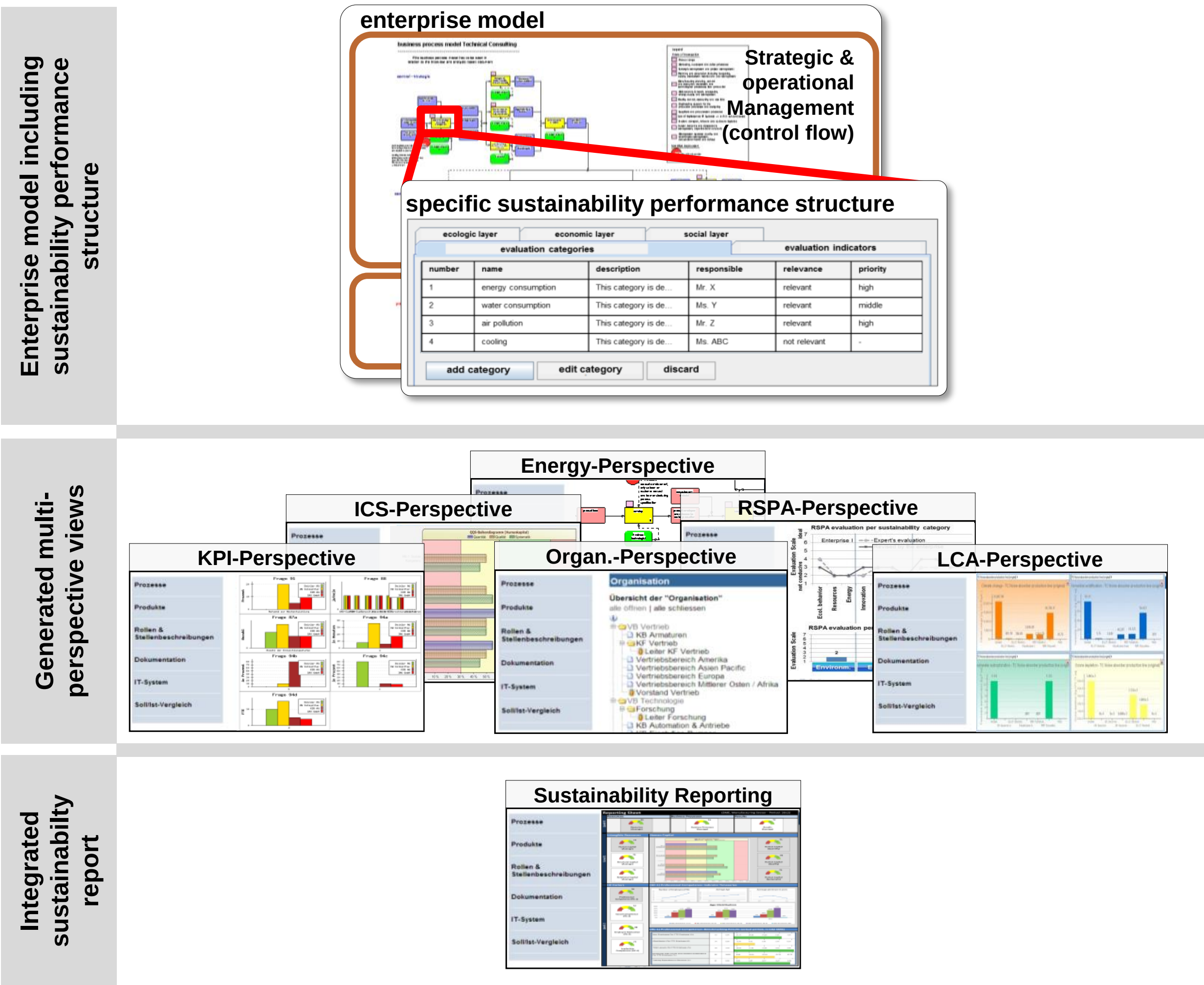


Figure 2: Structure of exemplary views for the Multi-perspective Modeling Approach

- marking of the enterprise control and management process (strategic, operational) which indirectly influence the high energy intensive processes (where something happens, where something affects)
- distribution of the energy consumption to certain criteria (e.g. physical location, organizational unit, source of energy etc.)

The specification of the different views is one step forward to the Multi-perspective Modeling Approach.

4 MODEL-BASED SUPPORT OF ENERGY AND RESSOURCE EFFICIENCY – A STATE OF THE ART

The investigation of existing approaches to handle energy and resource efficiency supported by models can help to support the development of the Multi-perspective Modeling.

Duflou et al. [9] give an overview of methods for increasing energy and resource efficiency in manufacturing. Regarding the impact of unit manufacturing processes, they note that existing life cycle inventory databases (LCI) usually comprise only few and only conventional processes focusing on primary material production and recycling. This fact can hamper energy and resource efficient process modeling. However, Duflou et al. [10] suggest an LCA-based methodology for creating unit process datasets for LCI within the CO_2PE program. As Duflou et al. [9] point out, commercial tools for simulating process chains or whole factories cannot yet include relevant energy and resource flows such as the flows of technical building services for assessing energy and resource efficiency.

Bunse et al. [11] analyze the gaps between scientific approaches to energy management in production and actual industry needs. Identified gaps exist in the area of enabling processes as energy efficiency is not sufficiently integrated into management systems and tools but also in the area of measurement as e.g. key performance indicators for assessing energy efficiency on process or plant level are missing. Bunse et al. reach the conclusion that available solutions for managing energy efficiency are not implemented in enterprises. An overview of different energy efficiency indicators is given.

As Smith and Ball [12] point out, there are no appropriate approaches for modeling material, energy and waste (MEW) flows, which allow quantitative analysis of the manufacturing operations of a company with regard to environmental impacts. They also notice that specifications for data collection for MEW modeling are missing, and that Life Cycle Assessment (LCA) and Value Stream Mapping (VSM) focus on the “product stream rather than production function” [12]. Based on their experience in a case company, Smith and Ball therefore develop guidelines for MEW process flow modeling intended to enhance the environmental efficiency of manufacture. These guidelines resemble the steps followed for the analysis presented here following these guidelines, Smith and Ball create two unconnected models with the same final aim of the company in different software: a qualitative MEW process flow map which assists in building the corresponding detailed quantitative spreadsheet model used for analysis. Control processes and mechanisms are included rudimentary in the qualitative IDEF0 map only.

Value stream mapping (VSM) offers a variant focusing on energy consumption as presented by [6]: energy value stream mapping (EVSM). This approach visualizes and analyses the energy consumption within a sequence of production processes in VSM manner. Here, every process is connoted with a data box with characteristic economical and energy-related parameters like process time, rate of yield, electric energy needs. For evaluation, the energy intensity and energy efficiency of the processes are analysed. Products are partitioned into product families and energy consumption is related to customer needs. There is a need for comprehensive parameter data is either measured at the corresponding machine or calculated. Management and other control processes as well as energy consumption of buildings, EDP systems etc. are not considered. Other resources than energy are neglected in EVSM but recently a CO2 value stream mapping method was presented by [13] which assesses the environmental impact of both material and energy. This method relies on model reproduction for LCA software though. A disadvantage of VSM is that it only works for one product flow and for a sequence of processes. Further, analysis of other potential states of a value stream map is not possible.

Keskin and Kayakutlu [14] combine energy based value stream maps (EVSM) and Bayesian networks for enhancing energy efficiency in small and medium manufacturing companies. They create a regular value stream map for the process chain of a product from which they subsequently omit “all processes which are unrelated to energy efficiency considerations” [14]. For the remaining processes, lines are added to represent the energy intensity and energy efficiency potential of the processes. This allows the detection of non-value adding energy consumptions in the process chain. Then, a Bayesian network is constructed highlighting the dependencies between different energy-related parameters. This step can be based on expert opinion when quantitative data is missing, as might be the case in SME. Using the Bayesian network, future state energy values stream maps can be created – e.g. by comparing different scenarios resulting from different changes in the non-value adding energy consumptions of certain processes. It is not elaborated how the energy efficiency potential of a process is defined and which parameters are connected to non-value-adding energy usage which serves as decision node in their Bayesian map. It is an interesting idea though to extend traditional EVSM by an efficiency potential and to develop a method for improving energy efficiency in SMEs which can deal without extensive sets of measured data. Management and control processes are neglected.

Seow and Rahimifard [15] present a framework for modeling energy flows within manufacturing systems from a product perspective as in life cycle assessment. Nevertheless, it allows “a breakdown of energy consumption within various processes” [15] using energy data at plant and process level. Seow and Rahimifard differentiate several types of energy such as direct, indirect, minimum and auxiliary energy. Indirect energy consumption is assessed for zones with similar indirect energy needs. Their calculations for assessing the total energy embodied in a unit product or the energy efficiency of processes are based on mathematical models provided for individual process types or on measurement results. A simple example model was implemented and a basic decision support tool created. Allocation methods and management processes are not considered. The product perspective is interesting though as it bridges process flow modeling and LCA.

The “Procedure for Energy and Material Balancing” (PEMB) suggested by Göschel et al. [16] also works with energy and material flows in order to enhance energy and resource efficiency in manufacturing process chains. It consists of four steps. First, the process chain is analyzed and single processes are specified regarding their type, technological parameters, equipment and their material and energy consumption. Then, the process elements, technological parameters and equipment are classified into the categories input, output, mechanism and control, and corresponding subcategories for each process. In order to calculate the input-output balances for the processes and process chain, experimental data or theoretical calculations are needed. For the balance, material and energy requirements are differentiated. Input energy is split into the active energy needed for the execution of a process and the basic energy needed for the standby state of the involved equipment. Output energy is determined for production of the product it-self and for its by-products. The balance results are used for evaluating the resource and energy efficiency, e.g. by identifying high-energy consumers or by comparing process efficiencies. Calculations can be performed for different scenarios. The approach focuses on the production layer of an enterprise. Management processes are not included in the method, which is intended as a tool for engineers. If implemented into suitable software, the method could support decision-making for higher resource and energy efficiency. But it only considers the amount of consumed energy or resources, not their environmental or economic impact. Detailed data on machine level is needed in order to perform PEMB, which requires comprehensive measurements or mathematical models.

Despeisse et al. [17] developed a workflow and prototype tool within the THERM project which can be used to model material, energy, water, waste and product flows not only through manufacturing operations but also through buildings and equipment in order to analyze and improve resource efficiency. Their approach includes a tactics library for improving resource efficiency, which was inferred from industrial practices. Tactics are generic rules for enhancing resource efficiency, e.g. “remove unnecessary resource usage” or “align resource input profile with production schedule”. An improvement hierarchy prioritizes the tactics in descending order from prevention, reduction and reuse to substitution. The hierarchized tactics library is intended to bridge the gap between existing broad sustainability concepts and specific operational sustainability practices. The workflow comprises the creation of a building model, the integration of a process model into the building model, back-up of the model with process data and operational profiles and finally simulated analysis of resource efficiency and potential improvement opportunities.

5 CONCLUSION AND OUTLOOK

The use case has shown that the associated application of enterprise modeling with energy and resource efficiency analysis generates added values compared to their separated application. For example, the description of energy and resource efficiency relevant content with the relating personnel staff, IT and documentation enable new evaluations and cross analysis, e.g. which staff is related to which energy consume. Moreover, the enterprise management processes can be integrated into the analysis. This requests a higher effort in the beginning of the data collection due to the amount of information and their level detail. But, this drawback can probably be compensated a) by smart supporting instruments assisting the data collection and b) due to the added values caused in additional evaluation capabilities. Nevertheless, a stronger integration of both spheres is recommendable. Based on the requirements a framework for a multi-perspective modeling method and respective support tools will be developed that enables understandable, operational views (“perspectives”) on sustainable value creation.

6 ACKNOWLEDGEMENT

We extend our sincere thanks to all who contributed to preparing this paper. Especially, we thank the German Federal Ministry of Education and Research for the funding of the project "Energy and resource efficiency for Russian SME" (support code 01DJ12086) as well as the German Research Foundation DFG for the funding of the Collaborative Research Centre 1026 "Sustainable Manufacturing – shaping global value creation" (SFB 1026/1 2012). The responsibility for the content of this publication lies with the author.

7 REFERENCES

[1] Reggelin T, Weinaug H, Referenzmodell Energie- und Materialeffizienz bei russischen KMU, Available at UFORDAT – Umweltforschungsdatenbank, internet database for environmental science from: http://doku.uba.de, (Apr 25, 2013).

[2] Kolomiichuk, S., Reggelin, T., Trojahn, S., Weinaug, H., 2013, Analyse und Verbesserung der Energieeffizienz produzierender KMU am Beispiel von vier russischen KMU, In: 2013, conference proceeding X. Internationale Wissenschaftlich-Praktischen Konferenz „Nachhaltige Entwicklung und effektive Ressourcenpolitik“,German-Kazakh University.

[3] Spur G, Mertins K, Jochem R, Integrated enterprise modelling. 1st ed. Berlin: Beuth Verlag GmbH, 1996.

[4] Mertins, K., Jochem, R., Jäkel, F.-W., A tool for object-oriented modelling and analysis of business processes, In: Computers in Industry, 345–356.

[5] Jäkel F, MO²GO - Enterprise Modelling, Analysis and Optimisation, Available from: http://www.moogo.de/, (May 10, 2013).

[6] Erlach K, Westkämper E, Energiewertstrom: Der Weg zur energieeffizienten Fabrik. Stuttgart: Fraunhofer Verlag, 2009.

[7] Jochem, R., Weinaug, H., Schäfer, M., 2012, Requirements, potentials and constraints of a semantic approach to model and access the sustainability within business processes, In: Seliger G., Kilic S.E. (Eds.), 2012, Towards Implementing Sustainable Manufacturing, 142.

[8] Rabe, M., Jochem, R., Weinaug, H., 2011, Multi-perspective Modelling of Sustainability Aspects within the Industrial Environment and their Implication on the Simulation Technique, In: Seliger G. et al. (Eds.), 2011, Advances in Sustainable Manufacturing, Springer Berlin Heidelberg, 315-320.

[9] Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S. et al., 2012, Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals - Manufacturing Technology, 61/2: 587–609.

[10] Duflou, J., Kellens, K., Dewulf, W., 2011, Unit process impact assessment for discrete part manufacturing: A state of the art, CIRP Journal of Manufacturing Science and Technology, 4/2: 129–35.

[11] Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M., et al., 2011, Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature, Journal of Cleaner Production, 19/6-7: 667–79.

[12] Smith, L., Ball, P., 2012, Steps towards sustainable manufacturing through modelling material, energy and waste flows, Sustainable Development of Manufacturing and Services, 140/1: 227–38.

[13] Erlach, K., Köhler, D.C.F., Süchting, M.A., Schrodi, T., Kuhlmann, T., 2012, CO2-Wertstrom, wt Werkstattstechnik online, 102/7/8: 518–22.

[14] Keskin, C., Kayakutlu, G., 2012, Value stream maps for industrial energy efficiency, In: Institute of Electrical and Electronics Engineers (IEEE) (Ed.), 2012, 2012 Proceedings of PICMET '12: Technology Management for Emerging Technologies, 2824–2831.

[15] Seow, Y., Rahimifard, S., 2011, A framework for modelling energy consumption within manufacturing systems, CIRP Journal of Manufacturing Science and Technology, 4/3: 258–64.

[16] Göschel, A., Schieck, F., Schönherr, J., 2012, Method for energy and resource balancing demonstrated as an example of the hot sheet metal production process, CIRP Annals - Manufacturing Technology, 61/1: 399–402.

[17] Despeisse, M., Oates, M.R., Ball, P.D., 2013, Sustainable manufacturing tactics and cross-functional factory modelling, Journal of Cleaner Production, 42: 31–4

18.7 Using ontology to support scientific interdisciplinary collaboration within joint sustainability research projects

W.M. Wang[1], A. Pförtner[1], K. Lindow[1], H. Hayka[2], R. Stark[1,2]

[1] Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany

[2] Virtual Product Creation, Fraunhofer Institute Production Systems and Design Technology Berlin, Germany

Abstract

A multitude of different perspectives and scientific disciplines have to be regarded considering research in sustainable development. Each discipline usually has its own understanding of sustainability and uses different vocabulary. Nonetheless, they have to work together to make a progress. To get a complete picture within the field of production, for example to evaluate the sustainability of a product or a process, different disciplines such as environmental engineering, mechanical engineering, mathematics or social sciences must be combined.

In the Collaborative Research Center 1026 – Sustainable Manufacturing an ontology is developed in order to link the different disciplines considering sustainable value creation networks. The ontology assists in exchanging information and data and thus fosters collaboration. The paper presents and discusses an extract of identified requirements and the approach on developing the ontology for collaborative research.

Keywords:

Ontology, IT-based Collaboration, Sustainability Research Projects

1 INTRODUCTION

With a growing public awareness for the finiteness of earth's resources and its consequences for global development sustainability has become a major research subject in recent years. Numerous research projects had been initiated worldwide addressing particular aspects of sustainability or respectively sustainable development.

In Germany, for example, the German national science foundation (DFG) among others has funded Collaborative Research Centers (CRC) bringing researcher from different scientific fields together to develop innovative production technologies (e.g. CRC 442 - Environmentally friendly tribosystems, RHTW Aachen, 1997-2009), product design methods (e.g. CRC 392 - Design for environment methods, tools and instruments, Technische Universität Darmstadt, 1996-2004) or organizational structures (e.g. CRC 467 - Transformable corporate structures of multivariant serial production, Universität Stuttgart, 1997-2005) in order to realize a more sustainable development.

With regarding to the reports of the so-called Brundtland-Comission (1987) and the Enquete Commission for 'Protection of human and environment' of the German Parliament (1995) sustainable development can be generally described as development 'that meets the needs of the present without compromising the ability of future generations to meet their own needs'. Eventually, 'the economic, ecologic and social dimensions of human being' have to be considered equally for the development of products, services and processes. [1] [2]

As the definition above implies, sustainable development closely entangles various perspectives and scientific disciplines. Hence, interdisciplinary collaboration is inevitable. On the other hand, collaboration between different scientific disciplines or institutions with their own respective culture and vocabulary can lead to communication and coordination problems and hinder the success of research projects [3]. A lack of common understanding may lead to misunderstandings or to the loss of potential synergies when research results are not linked sufficiently and/or relevant connections between partial results remain undiscovered. [4] [5]

To prevent such problems a common communication basis is needed to enable researcher (e.g. about concepts used in a project) and IT-systems (e.g. across different platforms) to communicate with each other. [6]

In context of the CRC 1026 – Sustainable Manufacturing (CRC 1026) an ontology is developed in order to create a common basis. This paper presents and discusses the first results of the ontology building process of the CRC 1026.

2 ROLE OF ONTOLOGY WITHIN THE CRC 1026

2.1 Set-up and objective of the CRC 1026

The CRC 1026 is an interdisciplinary research project funded by the DFG. It started in 2012 and consists of nineteen subprojects involving the four disciplinary science clusters of manufacturing, environmental engineering, economics and mathematics. The motto is 'From saturated markets, bridging the gap to hungry markets'. In fact, more than 60 researchers will collaboratively explore ways to face the economic, environmental and social challenges of future development by exploiting potentials of sustainable manufacturing and embedding them into global value creation. The subprojects, each addressing one specific aspect of sustainable manufacturing, are organized in three major project areas. [7]

Subject of Project Area A – Strategy Development is the identification and development of pathways for sustainable technology, their assessment, valuation and mathematical modeling. [7]

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

In Project Area B – Production Technology Solutions manufacturing processes and equipment, virtual systems for product development and organization of sustainable value creation in product and material cycles on different levels of aggregation will be realized exemplarily. [7]

Project Area C – Principles, Methods and Tools for Qualification links these perspectives by developing tools and methods enabling humans for learning and teaching help for self-help. [7]

2.2 Necessity of support for efficient collaboration within the CRC 1026

To fulfill the overall objective of the CRC 1026 research activities have to be coordinated and research results have to be combined. A number of potential cooperation fields had been mentioned in the proposal (Figure 1), which may be complemented by additional internal or external cooperation during the course of the entire research.

Without a holistic communication basis researchers might have to find a basis for each cooperation on a bilateral level and results may remain dispersed among different subprojects. Given the complex structure of the CRC 1026 such procedure would lead to inacceptable coordination efforts and hinder integration of cooperation results into the overall context. Thus, the creation of a shared understanding in an early stage of the project is crucial. A shared understanding can be represented by an ontology [6].

2.3 Potentials of ontologies

The term 'Ontology' is used to refer to the shared understanding of some domain of interest. An ontology necessarily embodies some kind of world view of a domain. Hence it can serve as a unifying framework to solve problems regarding

- communication between persons and/or organizations (e.g. provide a normative model),
- inter-operability (e.g. enable re-use and sharing of data / information / models between IT-systems) and
- system engineering (e.g. facilitate definition of requirement)

In context of the CRC 1026 an ontology can foster interdisciplinary collaboration in two perspectives. To reduce conceptual and terminological confusion the ontology can be used to create networks of relationships between all subprojects and their respective domains. The second perspective considers the constantly growing amount of data and results during the course of the CRC. In this perspective ontology can facilitate (automated) data exchange and data integration across heterogeneous IT-systems and institutions by serving as inter-lingua. [4]

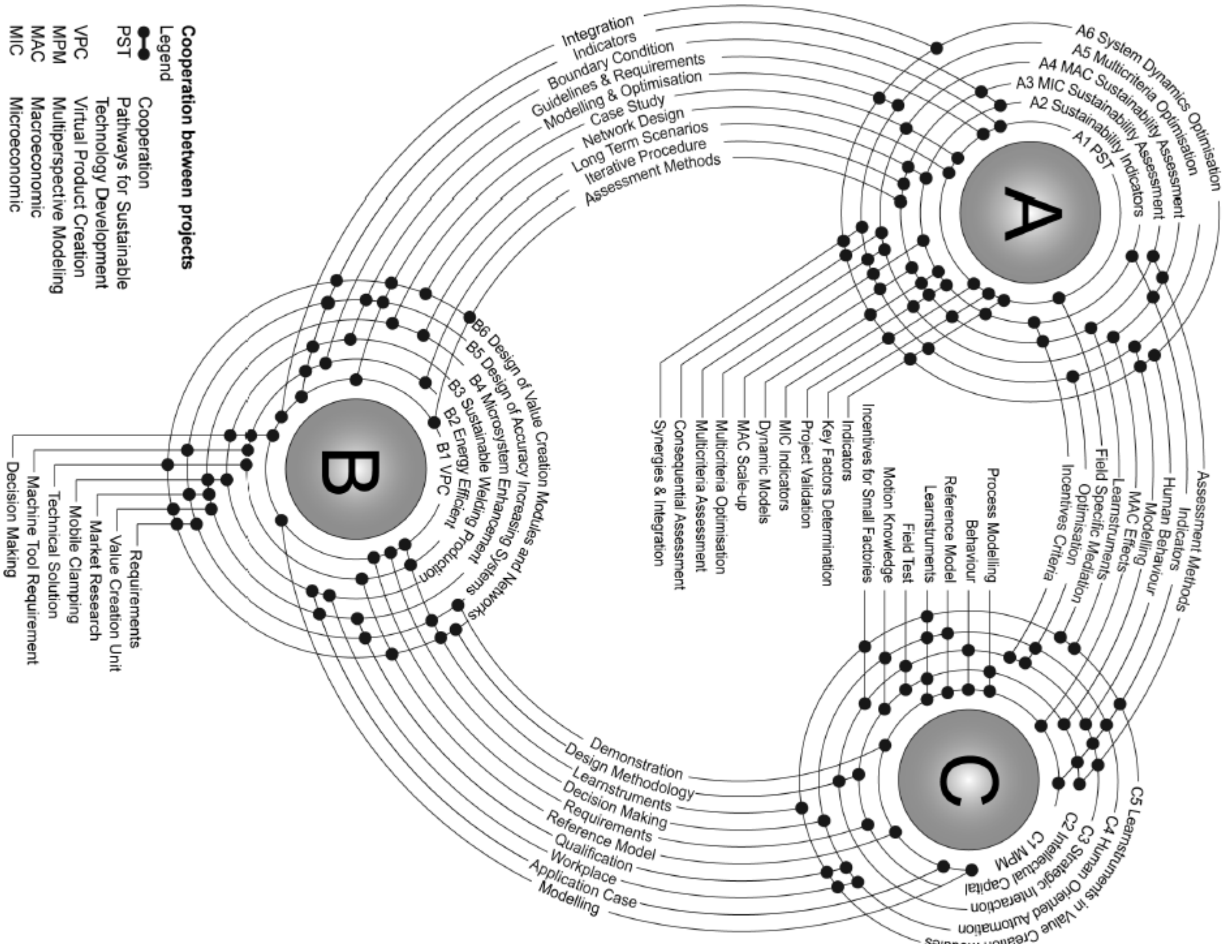


Figure 1: Potential cooperation within the CRC 1026 (graphic from [7, p. 21])

3 RESEARCH APPROACH

Before starting to develop the ontology, a suitable methodology was needed. Despite of a considerable body of experience in building ontologies, there is only few literature concerned with general methodologies for building ontologies. Instead various guidelines, hints and anecdotal experiences are reported. [8]

Approaches proposed in such reports vary in different aspects like the starting point of ontology building (e.g. from scratch or reuse of existing ontologies), the order of development steps (e.g. sequential or iterative) or how detailed concepts are defined. [9] [10]

However, there is still no consistent methodology for ontology building, as this process is rather 'seen as a craft than an engineering activity' [4]. Depending on the purpose of an ontology, the given prerequisites and involved parties, ontologies usually will be developed following individual sets of principals, design criteria and phases. [9]

At the beginning of the CRC 1026 general requirements for the ontology were rather ideas resulting from common sense than clearly defined sets of expectations. The authors of this paper, as members of the development team, stated the following constraints to guide the methodology selection:

- The ontology has to be built from scratch.
- It should support and foster collaboration within the domain of joint sustainability projects.
- The ontology has to be developed in cooperation with other subprojects. Thus, partial models have to be integrated later on.

Due to the lack of clearly defined requirements a generic four-phased-methodology developed by USCHOLD and KING was followed [8].

In the first phase the purpose of the ontology and the fields of application have to be identified.

The second phase contains three sub-activities to actually build an ontology. These activities are:

- Capture: Identify relevant concepts and their relationships.
- Coding: Transform the identified concepts into a formal language.
- Integration: Integrate existing ontologies.

These steps can have multiple iterations allowing incremental concept finding and coordination loops.

In the third phase the ontology will be evaluated and the fourth phase comprises the documentation of all activities. [8]

The USCHOLD and KING methodology provides a clear but generic guideline to create an ontology from scratch while its phases and development activities leaves room for customization according to individual needs. As the initial requirements for the CRC's ontology were not clearly defined this methodology provided a solid basis to start from.

4 PRELIMINARY RESULTS

4.1 Ontology Working Group

According to the model of USCHOLD and KING the purpose of the ontology has to be defined first. Therefore an Ontology Working Group (OWG) was established within the CRC 1026. It includes a core team that is responsible for coordinating and promoting ontology development and a group of 'consultants' that can be joined by every member of the CRC 1026 and external partners. The core team consists of the ontology development team and researchers who are involved with ontology development within their respective subprojects. The OWG further serves as a decision-making authority regarding questions concerning ontology development. However, the main objectives of the OWG are to lay the foundations of the ontology development process and to continuously coordinate development activities within the CRC 1026.

4.2 Results from the OWG

Definition of the general purpose of the CRC's ontology

Through group discussion a number of expectations towards the ontology were identified. It should facilitate collaboration by supporting:

- information exchange and/or aggregation,
- categorization of data / information / concepts,
- illustrating interdependencies between projects and/or concepts and
- exploration of different perspectives of concepts.

From those expectations two major use cases have been derived defining the overall purpose of the ontology.

1. *Ontology as glossary*: In that case the ontology's function is to serve as a glossary which allows researchers to refer to at any time. The terms in the glossary should be cross-linked to represent the interdependencies between the subprojects. Such a glossary should foster communication between researchers from different disciplines and institutions by providing a shared language base. Additionally, it can be used to establish a knowledge base for public audience in future. This use case requires concepts to be described in detail and in natural language.
2. *Ontology as inter-lingua / translator:* This use case considers that research results, which are created during the course of the CRC 1026, will be dispersed among different institutions and IT-systems. In order to realize IT supported combination of results, information aggregation and semantic search translators are needed to mediate between different IT-systems. That way, the ontology serves as a semantic foundation. As the ontology has to be machine interpretable the concepts have to defined in a formal language.

Consequently, the ontology of the CRC 1026 has to contain two parts. One part has to be readable by humans and the other part by machines respectively IT-systems.

Process to identify relevant concepts

For identifying relevant concepts there are three approaches described by USCHOLD and GRÜNNINGER [4]. The bottom-up-approach begins with very specific concepts that have to be condensed to more abstract concepts. This approach leads to a high level of detail and thus to higher and probably wasted development efforts as some concepts may not be relevant for the ontology. [4]

In contract, the top-down-approach starts with abstract concepts which have to be converted into detailed ones. With this approach it is easier to plan how detailed the concepts have to be elaborated, but it also may result in imposing arbitrary abstract concepts. [4]

A balanced course is the middle-out-approach as only the most important abstract concepts are captured initially and detailed specification of those are only done as necessary. [4]

In case of the CRC 1026 the OWG decided to follow the middle-out-approach. A challenge of the middle-out-approach is to define which concepts are 'the most important' ones regarding a specific purpose. To reduce the risk of omitting important concepts this activity had to go through several iterations.

In the first iteration concepts regarding sustainable manufacturing had been collected by the OWG in a brainstorming session. These concepts were then discussed and integrated into a common mind map (Figure 2). Similar concepts were merged and irrelevant concepts eliminated.

In a second iteration each member of the OWG was given two weeks of time to revise the initial mind map on his or her own, for example by adding or eliminating concepts and/or relations. This step should prevent important concepts from getting lost because of time limitations during OWG meetings. In a third iteration the OWG met again to integrate the edited mind maps into an extended mind map cooperatively.

In a fourth iteration the extended mind map was shared with the entire CRC 1026 in order to be reviewed and eventually complemented.

Based on the resulting mind map of the fourth iteration (Figure 3) a general discussion thread was started to extract the most important concepts. As a final result the following concepts were selected to represent the most important abstract concepts of the CRC 1026:

- Process
- Product Lifecycle
- Product
- Equipment and Facilities
- Human
- Information
- Instruments and Methods
- IT- Systems and Environment
- Organization
- Sustainability-Management

These concepts represent the basis for the conceptualization of the ontology.

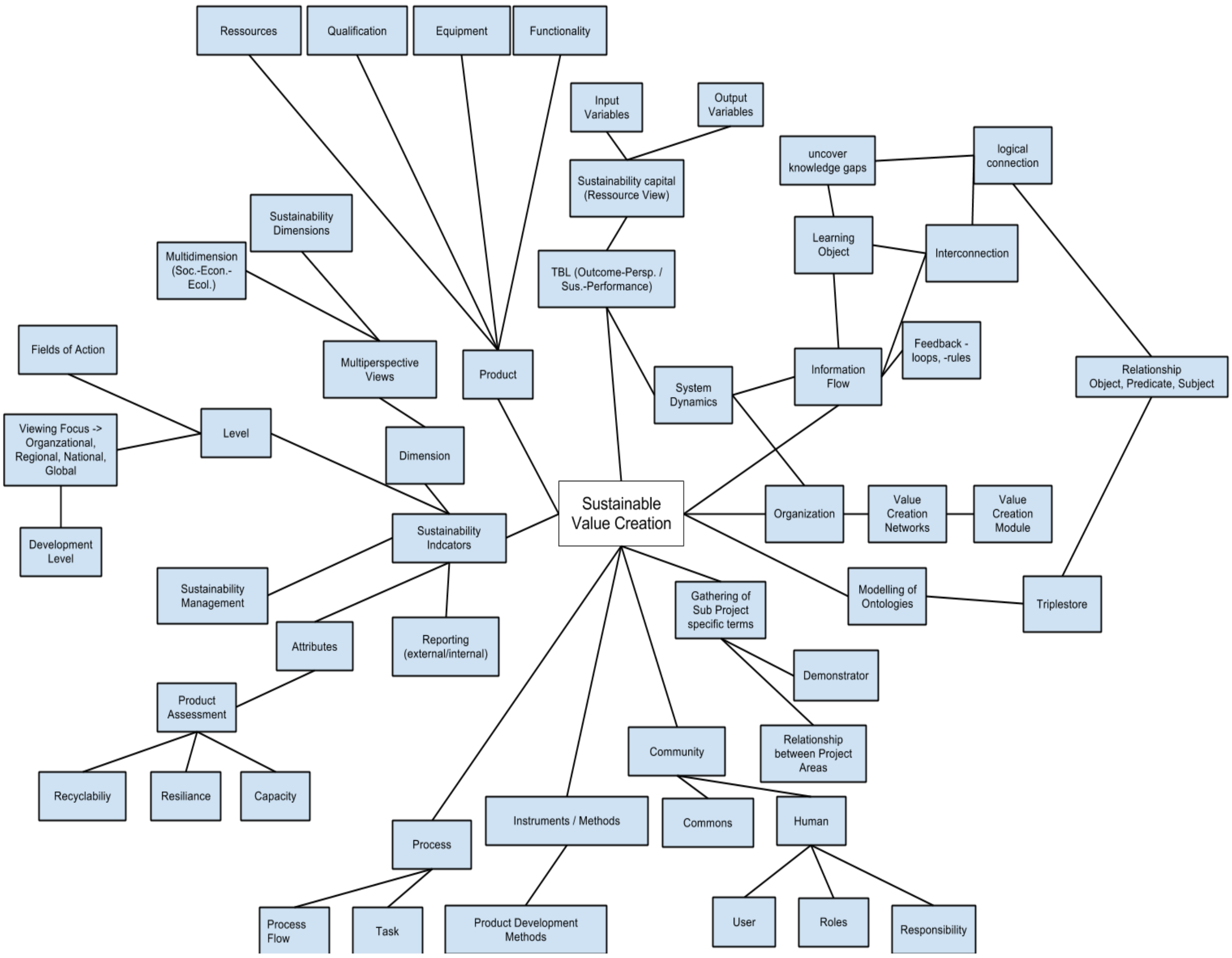


Figure 2: Excerpt of the initial mind map of main concepts of the CRC 1026

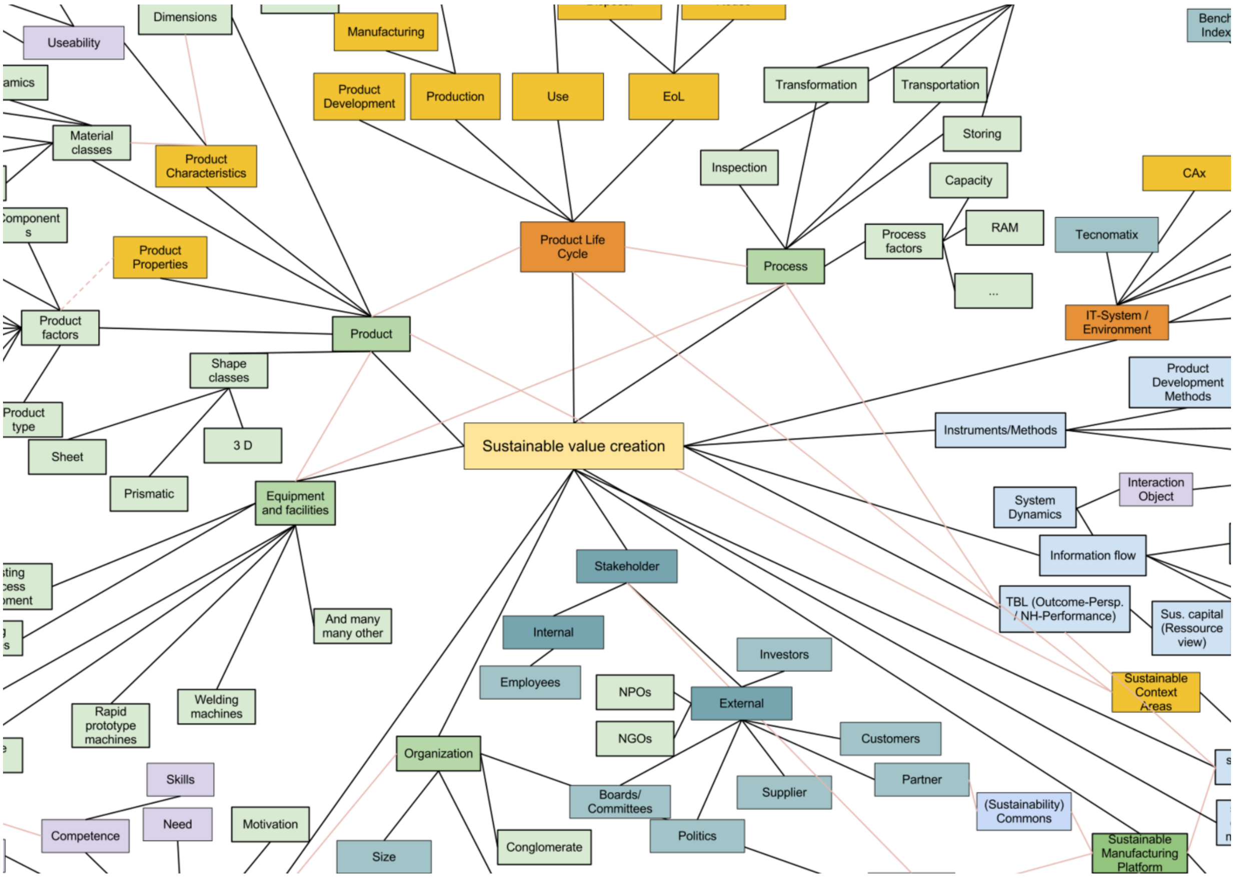


Figure 3: Excerpt of the extended mind map after iteration four

5 NEXT STEPS

5.1 Personal interviews

Despite of the requirements developed in the OWG the next step will be to conduct personal interviews with at least one member from every subproject regarding their expectations towards the ontology. One goal of these interviews is to explore particular requirements of the subprojects that were not identified by the OWG. Another goal is to evaluate the concepts acquired by the OWG and eventually to extend them. Concurrently, the OWG will continue its work. The interviews can be considered as supplementary activities to the OWG.

5.2 Building the conceptual base

To create a conceptual base for the ontology the identified concepts and their relationships have to be defined. For that purpose a wiki will be established. This approach seems to be suitable as text definitions (e.g. wiki pages) as well as relationships (e.g. by linking pages) can be represented. Additionally, it can be used as a kind of glossary mentioned in section 4.2.

5.3 Selection of representation language and modeling tool

In order to prepare for first codings a representation language and a modeling tool have to be chosen. In terms of ontology, coding means to transfer the identified concepts and relationships into a formal language. [8] A first review of existing tools suggests Protégé, an open source tool developed by the Stanford University, as a widely used modeling tool that uses OWL (Ontology Web Language) as representation language. For final decision making further tools and languages have to be investigated.

6 SUMMARY

Research on sustainability requires interdisciplinary collaboration. To achieve the goal of developing innovative solutions for sustainable value creation researchers of the CRC 1026 have to understand the complexity of interdependencies between subprojects. Currently, there is a general consensus that ontology can support collaboration, for example by reducing conceptual and terminological confusion. Still, particular strategies of how each subproject can benefit from a shared ontology have to be developed.

Although there is a considerable body of experience regarding ontology development, consistent methodologies on how to build ontologies are still missing, especially regarding sustainability research projects. Hence, generic methodologies like the methodology of USCHOLD and KING, can be used as guidelines. Depending on the purpose, the setting and other prerequisites of a project, phases and/or activities of the respective methodologies have to be customized.

Depending on the setting of a project (number of participant, scientific background) the identification of relevant concepts may need several iterations. Especially, the identification of the main concepts is crucial as those later represent the basis of the ontology. The top-down-approach as well as the bottom-up-approach may cause wasted efforts as they may result in too many detailed or abstract concepts which are irrelevant for ontology building. The middle-out-approach is a more balanced course.

7 ACKNOWLEDGMENTS

The research is funded by the DFG through the project "Sustainable Manufacturing- Shaping Global Value" (Collaborative Research Center 1026).

We thank all members and participants of the Ontology Working Group for great collaboration and for sharing their expertise. We also want to thank all researchers of the CRC 1026 for contributing to concept finding and reviewing.

8 REFERENCES

[1] E. A. Spindler, „Geschichte der Nachhaltigkeit: Vom Werden und Wirken eines beliebten Begriffes," 2011. [Online]. Available: http://www.nachhaltigkeit.info/media/1326279587phpeJPyvC.pdf. [Zugriff am 02. 04. 2013].

[2] Wissenschaftlicher Dienst des Deutschen Bundestags, „Der aktuelle Begriff - Nachhaltigkeit," 06. 04. 2004. [Online]. Available: http://www.bundestag.de/dokumente/analysen/2004/Nachhaltigkeit.pdf. [Zugriff am 02. 05. 2013].

[3] E. A. Corley, P. C. Boardman und B. Bozemann, „Design and the management of multi-institutional research collaborations: Theoretical implications from two case studies," *Research Policy,* pp. 975-993, 2006.

[4] M. Uschold und M. Grüninger, „Ontologies: Prinicples, Methods and Application," *Knowledge Engineering review,* pp. 93-165, June 1996.

[5] W. M. Wang, R. Woll, T. Damerau, K. Lindow, H. Hayka und R. Stark, „IT-based Concept for Collaboration within Joint Research Projects and Integration of Public Communities," *Proceedings of the10th Global Conference on Sustainable Manufacturing,* pp. 471-475, 2012.

[6] A. Pförtner , K. Lindow, H. Hayka und R. Stark, „Concept for decision-making support in sustainable product design based on semantic ontology," *Proceedings of the 10th Global Conference on Sustainable Manufacturing 2012,* pp. 476-481, 2012.

[7] TU Berlin, Fraunhofer IPK, Fraunhofer IZM, Federal Institute for Materials Research and Testing (BAM),Social Science Research Centre Berlin (WZB),Zuse Institute Berlin (ZIB), „Proposal for the establishment and funding of Collaborative Research Center 1026 - "Sustainable Manufacturing – Shaping Global Value Creation"," Berlin, 2011.

[8] M. Uschold und M. King, „Towards a Methodology for building Ontologies," in *In Workshop on Basic Ontological Issues in Knowledge Sharingheld, in conjunction with IJCAI-95*, 1995.

[9] M. Fernández-López und A. Gómez-Pérez, „Overview and analysis of methodologies for building ontologies," *The Knowledge Engineering Review,* Nr. 17:2, pp. 129-156, 2002.

[10] C. Reise, „Planung ingenieurwissenschaftlicher Qualifizierung mit Semantik-Web-Wissensbanken," Fraunhofer Verlag, Berlin, 2011.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

18.8 Sourcing automation to the crowds – by means of low cost technical solutions

J. G. Steingrímsson [1], G. Seliger [1]

[1] Department of Machine Tools and Factory Management, Technische Universität Berlin, Germany

Abstract

Increasing the level of automation in manufacturing organizations through low costing means should be a very lucrative option for those involved. Increased level of automation would mean higher productivity and could also mean higher quality, thus less lost opportunity cost, higher customer satisfaction, furthermore, less use of engineering materials that make up every tangible product. It is through crowdsourcing where every member of a certain community can contribute with their specific knowledge about a topic, towards innovative new ways of problem solving. The backbone of this specific crowdsourcing methodology is how it is structured by means of value creation module mapping, to a network. Contributions are designed and configured in a sequence of modules, offering the possibilities of comparison on a singular level or even a network level. This approach can be very useful for small and medium enterprises to remain competitive on the volatile global markets.

Keywords:

Crowdsourcing; Innovation; Low Cost Intelligent Automation; Value Creation Networks

1 INTRODUCTION

Modern automated manufacturing systems have driven productivity up and enabled the western world to remain competitive within the global product market. Automated manufacturing systems refer to systems that are capital intensive, where the organization's money is bound in equipment and systems such as motors, structural infrastructure, conveyors, sensors, actuators, PLCs and controls. On the other side of the spectrum are the manual manufacturing systems that are labour intensive, where money is mostly bound to wages of employees [1]. The automated manufacturing systems have been, by default more expensive than the manual ones, mostly due to the high degree of complexity of the automated manufacturing system. These systems have a much higher number of mechanical components, subassemblies, electrical components and higher degree of signal acquisition such as machine status, various energy and resource consumption. All these sets of subsystems have to be meticulously designed, procured and/or fabricated, assembled, tested, shipped, installed and commissioned before being taken to operational use.

The fabrication of such automated manufacturing systems is carried out by complex supply chains or value creation networks. Typically these networks consist out of various types of actors that are involved in the following steps of material extraction, material processing, manufacturing, retailing, disposal, remanufacturing and recycling, in between is the use phase, carried out by the product's user. Focusing only on the manufacturing actors, they can be seen as being involved in fabrication, subassembly, assembly and one that normally does the product's branding and then delivers the automated manufacturing systems to the system's operating facility. This process is in various steps, steps where manufacturing knowledge is heavily protected.

It is through the internet that information has the possibility to travel fast and to a widespread range of people. It is assumed that these people possess a wide spread of a specific technical knowledge, are motivated, able and willing to share this specific knowledge. Sharing the knowledge in the form of a community could change the view, the manufacturing industry has towards automation. Typically in order to obtain specific knowledge on some task, a member of the community either asks the other members of the community a specific questions on how to solve a specific topic or the member reveals to the community how it solved a specific topic. By this enabling other members of the community to try the solution out, give feedback or provide better means of solutions to that specific topic.

2 VALUE CREATION

Value is relatively complex matter and people differ in terms of how much artefacts and services are worth. Some people go to extremes to get the newest version of smartphones before the general public acquires them, standing in almost endless queues regardless of the weather conditions, while others prefer the less expensive same or similar versions from the competition. Value is to some extent the willingness of people to exchange another value, most commonly money for it. Kanji Ueda et al discussed value creation from a sustainable manufacturing point of view and how society could benefit from changing its view towards value. The genealogy of axiology was presented and how the knowledge of value had evolved from philosophical, individual, societal and environmental viewpoints. Their argument was that value is currently of an adaptive nature, that in contrast would be non-sustainable and that another approach towards value would have to be selected. This approach would be in the form of a conjoint value creation also referred to as cocreation, a concept where network externalities play an important role, by providing parts of the value creation [2].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

The relevance of sustainability as an integral part of modern manufacturing has been shown at various organizations. They can reduce cost, improve stakeholder relationships, reduce regulatory intervention and risk [3]. The importance of sustainability will continue to grow and the argument will become more and more valid that there is an addition to value creation when carried out in conjoint fashion [4].

2.1 Value creation Module

A way to express how value is created is through a value creation module (VCM). It is expressed by the five factors of it: As product, process, equipment, organization and human. The product specifies what the object is, the equipment specifies by what the object is manufactured, the organization specifies when and where, the process how and finally the human is the one who is carrying the value creation out. The products can be of various types of tangible artefacts that exchange perceived value from an output to an input, until the perceived output value at some point in time is lesser than the input value. At that point in time, when the product is considered not worth selling downwards the value creation or the end of life is reached, some other action has to be taken, such recycling, remanufacturing or different type of usages.

There is a complex interrelation between the five factors, the process requires specific equipment, the equipment relies on specific technology and the technology has to take various external factors into consideration. The equipment is housed in a facility and this facility requires various utilities to operate (e.g. electricity, gas, water, pneumatic air, hydraulics and consumables). Humans operate the equipment, under specific conditions (e.g. working hours per shift, shifts per week, according to remuneration plan, safety plan and hiring policy) but how this all works falls under the organization. The organization also manages the division labour, decides the extent to which processes are vertically or horizontally integrated. Graphical representation of the value creation module is shown on Figure 1 [5].

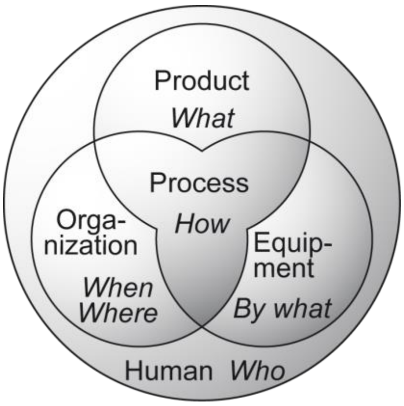


Figure 1: A value creation module [5]

Connecting value creation modules enables for the representation of value creation chains or value creation networks where more than two value creation modules are connected together. As automated manufacturing systems are heavily dependent on processes and equipment, only those two will be depicted:

- Processes: They specify how products are manufactured. The processes come in a sequence, traditionally the output of one process becomes the input of the next process until finished parts, subassemblies or desired finished products are readily available. Manufacturing processes are classified in the main operations of transformation, transportation, storing and inspection. Many process types can be carried out in a different type of manner, such as cutting process that can be carried out by means of a hacksaw, a band saw, a lathe or even a CNC machine.
- Equipment: In order to carry out the different types of processes, specific types of equipment are required. The equipment is based on different types of technology and/or functionality and even different brands.

2.2 Value creation chains

Manufacturing systems can be seen having five different levels depending on the perspective of the organization. These levels are device/unit process, line/cell/multi-machine system, facility, multi-factory system and enterprise/global supply chain. The three first levels of interest to this paper are depicted as following [6]:

- Device/unit process: Single machines, equipment, devices or machine tools that perform desired functions. Including support tools such as jigs, fixtures, moulds, clamps and measurements tools, furthermore, instrumentation such as gauges, sensors, actuators and control units. This level can also be considered as a single value creation module.
- Line/cell/multi-machine system: Series of device/unit processes that performs an intended function of producing parts, components or subassemblies, though not the intended output of the factory. This system can be viewed as a value creation chain.
- Facility: The desired output of the factory is carried out within a facility. It can be parts, components, subassemblies or finished products. A facility is a good example of a value creation chain.

Representing value creation chains on the above mentioned levels, where the focus on the processes as a primary connection point offers the possibility to create a modelled representation of the process. Figure 2 represents the value creation chain, the value creation module from Figure 1 is there shown in miniature version of it to show the process flow from the first process to the last.

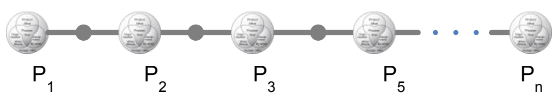


Figure 2: Model of a value creation chain

Each stand-alone unit process instantiation is represented with the equipment it requires such as motors, structural infrastructure, conveyors, sensors, actuators, PLCs, controls and measurement units. Single standing unit processes such as sensors and multifunctional unit processes such as PLCs are represented separately. The integral function of each process determines whether or not it is represented as a unique value creation module.

3 MANUFACTURING SYSTEMS

The term manufacturing system refers to a system that transforms necessary inputs, such as raw material, parts, components, subassembly, assemblies and energy, into desired equal finished outputs. These desired outputs are then in significant amounts sold onwards and what is referred to as downstream, towards the buyers of these outputs.

3.1 Automation

The term automated comes from automation and is defined according to the Merriam-Webster on-line dictionary as: "Automation has the possibility to increase precision and accuracy compared to what can be achieved through manual workers" [7]. Automated in that context refers to equipment, a process, or system that operates by automation. Full automation should then replace all human labour for the specific operation the automation covers and semi-automation is a process where some level of automation exists. Automation has the possibility to increases precision and accuracy. Compared to what can be achieved through a manual workers.

A conventional view is that as there is a trade-off between automation and flexibility, i.e. as automation rises the flexibility decreases. Lotter and Wiendahl presented in 2009, a model where three levels of automation (manual assembly, hybrid assembly and automated assembly) are presented as areas and located in between the spectrums of flexibility, quantity, quality and variant diversity as presented on Figure 3 [8]. Even though the tasks refer to different assembly procedures, these different spectrums are applicable to the processes that fall under the scope of this paper and main focus will be on hybrid assembly to automated assembly setups, where quality and quantity is important.

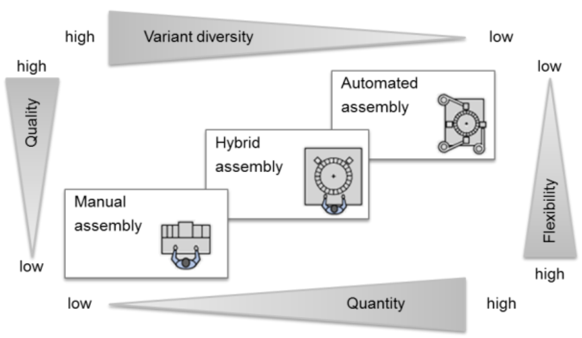


Figure 3: Utilization areas for manual, hybrid and automated assembly concepts [8]

Manual tasks are best suited to low quantity where high variant diversity can be expected. This requires a high degree of flexibility from the operational and organizational structure but lower quality of the end product can be expected. Automated tasks are best suited to high quantity where low variant diversity exists. The highest degree of quality can be expected but due to the system's restrictions it has a low degree of flexibility. Hybrid tasks (semi-automated tasks) fall in between manual and automated tasks, with medium quality, flexibility, quantity and variant diversity.

3.2 Complexity of Systems

The spectrum for automated manufacturing systems covers simple configurations to complex system configurations. Complexity is influenced by the quantity of information, the diversity of information and the information content. Generally speaking, processes complexity increases with the lack of clear requirements and the unreliability of tools. As processes and tools become more reliable the complexity of the process systems reduces [9].

Monument is a terminology for objects of such proportion that they are unmovable and which will stand the test of time. Generally monuments referred to type of structures that are either created to commemorate an important historical person or an event of important or horrific historical proportion for a group of people. In the manufacturing industry it is used in a negative manner for a wrongful selection of machinery, with considerable amount of costs attached to it. Traditionally they are equipment such as heat-treatment ovens, paint sprays equipment and large automated machining centres [10].

Right sized tools are tools that are neither too little or to large. An example for right sized tool is a toothbrush. It fits perfectly between the palm and fingers and is capable of performing the task of brushing all the teeth, including the jaws. In the manufacturing industry it is mainly used for simple and low cost machinery that is capable of performing processing tasks in a compatible manner compared to more expensive machinery. This machinery sometimes requires modification to it.

3.3 Low Cost Intelligent Automation

The origin of Low cost intelligent automation (LCIA) comes from Hitoshi Takeda, a term that was coined in the 1990s. LCIA is primarily applied in assembly, mechanical processing and in-plant transport. LCIA describes a process where pre-existing machinery is equipped with simple mechanical appliances that augment the function of the pre-existing machinery such as by ejecting parts from the machinery after work has been carried out on it and/or transporting the part from it. An example is an automatic release mechanism coupled by means of lever mechanism or sensors to a stand drill. When the drill reaches a certain predefined position, the drilling is subtracted, the stand drill shuts down and the work piece is ejected from the fixture holding it in place through the process. LCIA is superior to full automation because production facilities may be rearranged and newly combined according to different value streams in a much easier way, this makes ensure that the machinery will not become a monument [11].

4 OPEN INNOVATION AND CROWDSOURCING

There is an immense amount of information that is either being sought after and exchanged on the internet, where more than 2 billion e-mails are sent, more than 2 million queries are made on Google, more than 2 thousand FourSquare users perform check-ins visits every minute and AgentAnything receives around a one unique visits every two minutes. The AgentAnything website, offers the citizens of New York and New Jersey the possibility to have almost any task carried out for them. The tasks or the missions as they are referred to have to be defined and an agent, someone, has to be willing to do the task. Tapping into only a small proportion of this huge knowledge exchange would be very lucrative for organizations.

Open innovation occurs when companies open their boundaries to the outside in order to seek different, improved or new ideas to problems they have. This process is depicted in a graphical representation on Figure 4, originally drafted by Professor Henry Chesbrough but for the sake of this paper it is adapted. Open innovation is generally highly dependent on the customers [12]. Open design is a form of open innovation, and come in various forms such as open manufacturing, open prototyping, open idea generation, open community projects, open downloadable design and open design tools [13]. There are three core practices for integrating customers to open innovation: Lead-user method, internet toolkit and idea competitions. The lead-user method is an invitational (receive an exclusive invitation to participate), directed (given no instructions) or suggestive (given no instructions) approach where few experts or lead users are invited to carry out the innovation. The internet toolkit as the name implies is when the users are obtained through internet portals. This process can be directed or suggestive and mostly participative, i.e. everyone can participate. The last form is idea competitions where there is a specific topic, requiring a solution. The idea competitions are often used early in the innovation process, participative and carried out in a directed or suggesting form [14],[15]. Difference to the other two the idea competition offers direct incentives for the best results and depending on the types of motives and incentives. The motives are learning, direct compensation, self-marketing and social motives. It is through motives that open design can be manipulated and the activation of participates triggered. A proper design of the components for activation and participation support is required [14].

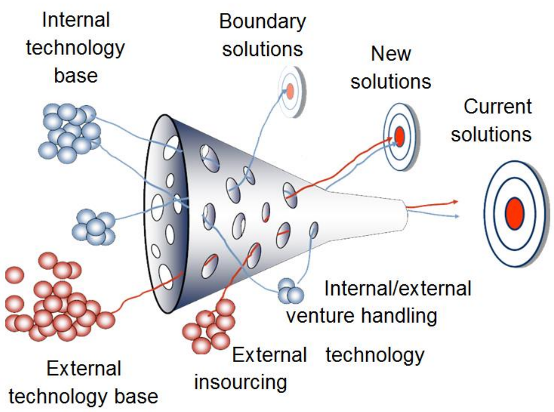


Figure 1: Open Innovation (Original source: Professor Henry Chesbrough)

Hopkins in 2011 specified the act of crowdsourcing as having a task usually performed by a designated individuals or groups of individuals, such as employees and outsourcing that task to an undefined group of people in the form of an open call [15]. Crowdsourcing contains a collaborative nature since people, that under normal conditions would not work together are working together. Even the customer can join the value creation as previously described here above, e.g. when contributing to a product innovation. On the other hand due to the fact that there is no formal long term agreement between the people working together on the crowdsourcing, there is a competition element embedded in this arrangement [16]. Through an open innovation such as crowdsourcing, a larger solution space is opened than what is accessible through the internal technology base. Figure 4 presents an adapted version of the widely accepted open innovation process that fits the value creation modelling. The red and blue spheres represent VCMs. The funnel is the organization's boundary, that would under closed innovation conditions no be penetrated but under the open innovation the boundary is open to different bases of knowledge and skills. Here it is assumed that by opening the internal VCM base, new and alternative different solutions can be generated [17].

What open innovation might means for small and medium enterprises (SMEs) is an access to competences that they normally do not possess and are not capable of maintaining. The necessary expertise can be sought after when required, even in specific intervals suiting their available investments [18]. Important for the SMEs, is to specify the requirement for each task they have for the crowds. Newly acquired competences also pave the way for dialogs with larger enterprises or new markets [14]. Policymakers within the OECD also agree with the importance of collaboration with external partners and open innovation, as it is one of the highlighted seven main policy areas for SMEs [19].

4.1 Crowdsourcing Examples

There are currently various examples where open design works, examples are 3D printers, robots, laser cutters, machine tools, CNC machines, electronics and many more. To name specific projects then the RepRap (http://reprap.org) project, that has the goal to print printed circuit boards by means of additive manufacturing. The RepRap project has been going on for several years now and during this time immense improvements have been done by the community behind the project. Another well worth mentioning project is the Global Village Construction Set (GVCS, http://opensourceecology.org/gvcs.php). It is a network of farmers, engineers and enthusiasts. It is an open design for manufacturing initiative where the contributors have designed over 50 machines and built several of them, such as bulldozer, soil pulverisers and presses. Even though the GVCS is an open design platform it already shows how modern technology can be built with a proportion of the cost of buying similar machinery from an original equipment manufacturer. A very well-known crowdsourcing scheme is the one of the European Commission that carries out crowdsourcing of open calls through its research programme framework. For each call there has to be made a proposal. The calls have requisitions in terms of composition of parties (i.e. industry, universities and research institutes), number of parties and quality of how well the proposal fits the call. Unique for this type of crowdsourcing is that successful proposals are funding during duration of the project. The reason is the amount of capital and time bound to the project, since few would have the financial capacity to work on a project for months and only receive payment once the project would be completed [20].

Examples of crowdsourcing activities that are closer to the use case considered in this case are based on a structure similar as the VCM's structure: Who, what why and how. Wikipedia has an undefined group (the who), deals with public goods or wiki-articles (the what), intrinsic incentives (the why) and in a collaboration (the how). Yahoo! Answer is a portal for the best answer according to the portal's users, the contributors are undefined groups that seek out problems for public goods, for multiple incentives based on a competitive setup [21]. Innocentive (http://www.innocentive.com/) is a platform that connects specific groups of people with companies with problems on private goods for an extrinsic incentive (payment), where the solutions are gathered in a collective manner. Amazon Mechanical Turk (https://www.mturk.com/mturk/) is a platform for undefined groups of people dealing with private goods for payment as well as with the Innocentive problem in a competitive manner.

SME-related activities on crowdsourcing platforms are numerous, most of them new start-ups. One such platform is ideaken (http://www.ideaken.com/) that offers a closed platform between a problem seeker (a company) and a network of problem solvers (group of individuals). A problem solver receives remuneration, once the company is satisfied with the solution.

4.2 Crowdsourcing LCIAs

Crowdsourcing of any problem poses various challenges. There has to be a clear understanding on whose attention to attract, its qualification, if there should be any ties to specific types of organizations, furthermore, what should be the incentives and how to measure how well the task has been carried out.

The challenge of LCIAs is how to deal with complexity that means should the call be limited to a single machine or a setup of machines. What is the success criterion of the call, i.e. should the main objective be to reduce costs, compared to similar on-the-market solutions or provide cost reduction through a shift from labour intensive operations towards more capital intensive operations. The proposal of this paper is to utilize the sustainable manufacturing platform to set up or seek out value creation modules for crowdsourcing purposes, specifically on hybrid systems that have some degree of automation but are dependent on human labour. Complex systems should be avoided in the beginning, focusing on breaking down systems to smaller sizes. Having clear understanding on the manufacturing systems and which equipment to replace is vital, therefore, the value creation module mapping behind the sustainable manufacturing platform comes in handy. It enables the comparison of solutions and backs up the decision making process. Other dimension that the platform offers is a comparison of solutions that contain advantages in terms of environmental value, pragmatic or psychological on top of the economic value addition already being considered internally within the system.

4.3 Sustainable Manufacturing Platform

The applicable sustainability surroundings for LCIA crowdsourcing tasks are local production, inclusion of developing countries and consumer's involvement in product's design and improvement. It supports economic growth and development through locally available resources, created through solutions made available through open innovation [22]. Through locally available resources, shorter material loops are made available and through greater reutilization and recycling efforts a net environmental improvements can be gained [23]. This combination provides the means to produce products of higher quality compared to before, improving human wellbeing at reduced consumption rate for non-renewable material sources.

As the previous examples show there is a need to specify the calls properly and address them to specific target groups. Heyer et al in 2013 proposed the utilization of the sustainable manufacturing platform (SMP) in order to collect knowledge, store the knowledge in the repository, thus making it usable for the members of the platform. Figure 5 shows a framework of the knowledge pool for sustainable manufacturing. The SMP could be used in various fields and different places of the world, e.g. in the less developed parts of the world in order to improve living conditions of people [23]. The target group for the LCIA would be undefined groups of people with special industrial and automation knowledge, willing to share their knowledge with others. The incentives for the contributions would be in the form of evaluation score (i.e. feeling of competence) and the prospect of improving the lives of others in a collaborative manner. The system enables feedback to the users, so that the users gain more knowledge by sharing ideas and experience of use. What remains is to establish the breakdown of the manufacturing system's elements to be improved with LCIA. The SMP system's requirements enable the setup of different types of information details ranging from unit level to a facility level.

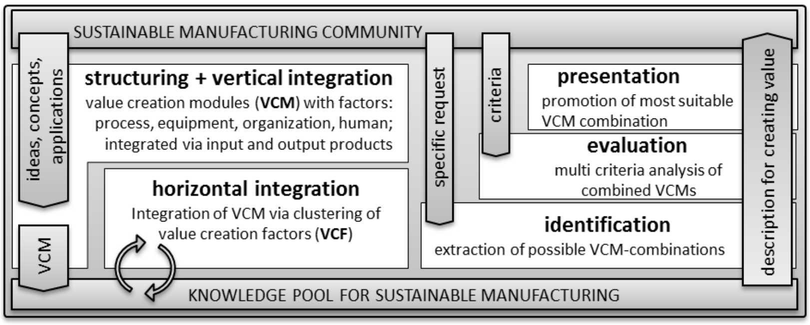


Figure 5: Framework – Sustainable Manufacturing Platform (SMP) [23]

4.4 Limitations

Besides the organization's fear of losing knowledge or letting their competitors know too much of their core competences there are several limitations to this proposed methodology. The manufacturing industry has a reputation of having a lack of openness. In order to carry out crowdsourcing there has to be designated stakeholder expediting the desired results and the person carrying the task out has to have a clear idea of what is expected as a result. As previously stated LCIA has a limited span of application fields. The open design movement that could be attractive for SMEs seems to be in the development phase, not fully ripe and several questions remain unanswered, such as regarding property rights and security of data.

5 CONCLUSION

Automation has great potential in replacing human operators in tasks that are physically difficult or even beyond human capacities, in tasks that are monotonous, and in dangerous environments (e.g. bomb threats, fire, underwater). From an industrial point of view the objectives is nevertheless, to reduce labour costs and improve quality. Automation comes at a cost and simultaneously binds capital, where system integration is important. In order to increase the change of crowdsourcing activities they have to be assigned for the right people under the right boundary conditions [21]. Essential is to select the correct incentive-support components in order to stimulate activation and participation [14]. This paper presented how low cost automation opportunities for SMEs can be inserted on the SMP, a call made in order to start analysing the problem. LCIA contains great opportunities but in order to realize them the VCM have to be modelled sufficiently and the specific processes requirement published in the form of an open call.

6 ACKNOWLEDGMENTS

We extend our sincere thanks to all who contributed to preparing this paper. Especially, we thank the German Research Foundation for the funding of the Collaborative Research Centre 1026 “Sustainable Manufacturing – shaping global value creation” (SFB 1026/1 2012). The responsibility for the content of this publication lies with the author.

7 REFERENCES

[1] Abele, E., Meyer, T., Näher, U., Strube, G., Sykes, R. 2008. Global Production – A Handbook for Strategy and Implementation. Springer, Berlin.

[2] Ueda, K., Takenaka, T., Vancza, J., Monostori, L., 2009. Value creation and decision-making in sustainable society. In: CIRP Annals - Manufacturing Technology, Nr. 58, Volume 2, pp. 681-700.

[3] Epstein, J., 2008. Making Sustainability Work: Best Practices in Managing and Measuring Corporate Social, Environmental and Economic Impacts. Greenleaf Publishing Limited. Sheffield.

[4] P2P Foundation, 2012. Synthetic Overview of the Collaborative economy.

[5] Seliger, G., 2007. Sustainability in Manufacturing, Springer Verlag Berlin Heidelberg. Berlin.

[6] Duflou, J. R., Sutherland, J. W., Dornfeld, D. Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012. Towards Energy and Resource Efficient Manufacturing: A Processes and Systems Approach. In: CIRP Annals - Manufacturing Technology, Nr. 61, Volume 2, pp. 587-609.

[7] “Automation”, 2013, in Merriam-Webster.com, Merriam Webster online dictionary, accessed: 19.04.2013. <http://www.merriam-webster.com/dictionary/automation>

[8] Lotter, B. and Wiendahl, H. –P., 2009. Changeable and Reconfigurable Assembly Systems. In ElMaraghy, H. A. (Ed.) Changeable and Reconfigurable Manufacturing Systems (pp. 127-142). Springer, London.

[9] ElMaraghy, W., ElMaraghy H., Tomiyma, T., Monostori, L., 2012, Complexity in Engineering Design and Manufacturing, 62nd CIRP General Assembly, Hong Kong, China, August 2012 Keynote Paper.

[10] Maskell, B., Baggaley, B., Grasso, L., 2011. Practical Lean Accounting: A Proven System for Measuring and Managing the lean enterprise. CRC Press, Florida.

[11] Takeda, H., 2004. LCIA - Low Cost Intelligent Automation. Redline Verlag. Munich.

[12] Chesbrough, H. W., 2003, Open Innovation: The new Imperative for creating and profiting from technology, Harvard Business School Press, Boston.

[13] Geyer, M, Reise, M., Manav, F., Schwenke, N., Böhm, S., Seliger, G. 2012. Open design for manufacturing - Best practice and future challenges. In: Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey.

[14] Leimeister, J. M., Huber, M., Bretschneider, U., & Krcmar, H. (2009). Leveraging crowdsourcing - activation-supporting components for IT-based idea competitions. Journal of Management Information Systems, 26(1), pp. 197–224.

[15] Hopkins, R. (2011): What is Crowdsourcing? In: Sloane, P. (eds.): A guide to open innovation and crowdsourcing, Kogan Page. London.

[16] Kleemann, F., Günter Voß, G. 2008. Un(der)paid Innovators: The Commercial Utilization of Consumer Work through Crowdsourcing. In: Science, Technology & Innovation Studies, Nr. 1, Volume 4.

[17] Chesbrough, H., 2003, Open Innovation – The New Imperative for Creating and Profiting from Technology. Harvard Business School Press. Massachusetts.

[18] Maiolini, R., Naggi, R., 2010, Crowdsourcing and SMEs: Opportunities and challenges. In: Proceedings of the 7th itAIS, 2010.

[19] OECD, 2010, OECD Studies on SMEs and Entrepreneurship – High-Growth Enterprises, What government can do to make a difference. OECD Publishing.

[20] “Cordis - Community Research and Development Information Service”, 2013, in http://cordis.europa.eu/fp7/home_en.html, European Commission, accessed: 06.05.2013.

[21] Zhao, Y., Zhu, Q., Evaluation on crowdsourcing research: Current status and future direction, Inf. Syst. Front. Springer.

[22] Bauwens, M., Iacomella, F., and Mendoza, N., 2012, Report: A Synthetic Overview of the Collaborative Economy, Orange Labs and P2P Foundation. Retrieved online from: http://p2p.coop/files/reports/collaborative-economy-2012.pdf

[23] Heyer, S., Steingrímsson, J. G., Seliger, G., 2013, Identification and promotion of effective and efficient product and material cycles via crowdsourcing. In: Proceedings of the 20th CIPR Conference on Life Cycle Engineering (LCE 2013), Singapore, Singapore.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

18.9 Learnstruments in value creation and learning centered work place design

Randy McFarland[1], Carsten Reise[1], Aleksandra Postawa[1], Günther Seliger[1]

[1] Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany

Abstract

Increasing awareness of sustainability across the broad span of stakeholders involved in the value creation process is one challenge in manufacturing. The value creation participants will emanate from a multitude of globally divided regions, cultures and educational backgrounds if wealth and value creation is to be more evenly distributed throughout the world population. This in turn results in a significant increase in the required teaching and learning efforts. This paper will focus on achieving this increase through the development and application of so called learnstruments in combined learning and working environments. Learnstruments are artifacts and systems which automatically mediate their functioning to their user. The authors present a method for determining and assessing such systems as well as exemplary cases from the area of manual assembly and repair work places.

Keywords:

Knowledge engineering, Learning factory, Sustainable manufacturing, Usability, Work place design

1 INTRODUCTION

Increasing awareness of sustainability for adequate action and decision making across the broad span of current and perspective stakeholders involved in the value creation process is one challenge in manufacturing. The value creation participants will emanate from a multitude of globally divided regions, cultures and educational backgrounds if wealth and value creation is to be more evenly distributed throughout the world population. This in turn results in a significant increase in the required teaching and learning efforts, as this multitude of participants must be continually informed about new and ongoing developments in sustainable manufacturing. Additionally, mega trends globalization and demographic change pose the challenges of continuous learning and qualification of the worker and innovative methods for transferring the knowledge of more experienced workers [1]. Abele et. al have identified Learning Factories as an innovative approach to meeting this challenge. While the concepts proposed here can be utilized for the development of work systems within a Learning Factory concept, the focus here will be on work place design and not on work place organization or qualification management. This paper will focus therefore on achieving an improvement in learning productivity for learning at manual assembly and repair work places through the application of so called learnstruments. Learnstruments are physical artifacts applied in working and learning environments for working and learning tasks. They are characterized by an intrinsic property of mediating knowledge about their functionality to the user through use [2]. This property is realized in design by introducing functions, whose purpose is the visual, audio and haptic transfer of this knowledge, so called mediation functions. Design solutions for these functions are chosen according to their applicability to the type of learning required. This method for developing and evaluating learnstrument concepts according to their mediating functionality will be presented.

2 APPROACH

2.1 Combined learning and working environment

The research project *Learnstruments in Value Creation Modules* (see Section 7) examines work place qualification. The generic work place serves as a central field of application for learnstruments. The learnstrument concept addresses a combined learning and working environment. The working and learning tasks are no longer separated, but integrated within the working process. Their application becomes economically competitive when this type of intelligent/ learning centered design of processes, equipment and organization is less expensive than supplementary or redundant training systems and materials. Systems which meet these criteria could then be applied to also mediate new approaches to sustainable manufacturing, such as production energy conservation, directly at the work place.

The main elements of the respective environments are combined as shown in Figure 1. The learner partakes in a learning process. Within the learning environment, he or she completes the learning task with the aid of the learning material. The result of the learning process is the learning output. The successful application of the learning output in further tasks is the learning outcome [3]. Structured learning process may result in a qualification of the learner or in the acquirement of specific skills; these processes are generally called qualification and training processes respectively [4]. The counter process to the learning process is the teaching process. The worker fulfills the working task. Within the working environment, he or she utilizes equipment for this purpose. The result is generally material goods or services and the completion is remunerated [5].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

ISBN 978-3-7983-2609-5

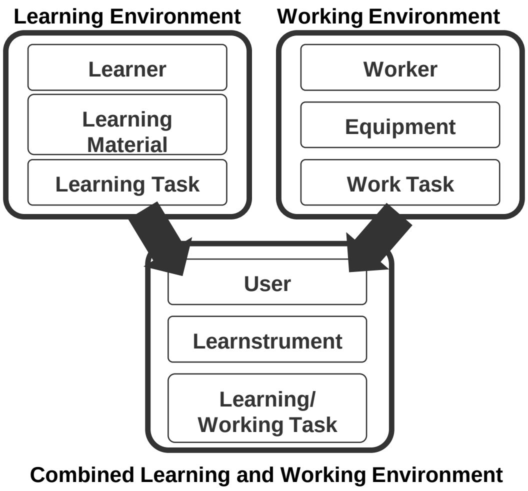


Figure 1: Learnstrument environment with key elements

In the combined working and learning environment, the user fulfills the learning and working tasks under application of the learnstrument. In [6] the authors provide a typology for type of use, target groups and content for work system in the form of Learning Factories. In the following, the authors will adhere to the described classes for target groups, operational staff, engineer, manger, student and research staff as well as the classes for content process improvement, diagnosis, system design and quality control. These classes will be understood as the users and learning/working tasks respectively. The users benefit from both the hands on skill building through learnstruments and from the availability of online teaching resources allowing them to independently design their learning paths and qualification profiles [7].

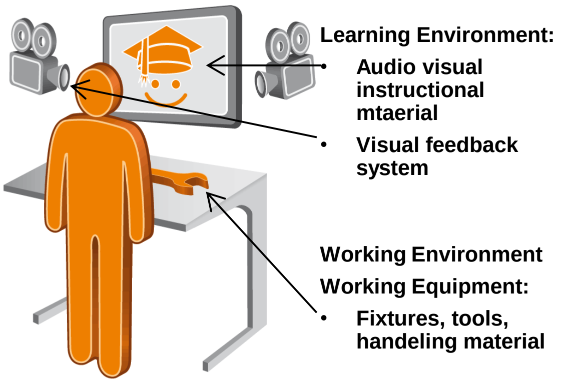


Figure 2: Learnstrument environnement for manual assembly

2.2 Increasing Teaching and Learning Productivity

The productivity of teaching and learning is a qualitative term defined by the ratio of teaching input to learning outcome. The input can be quantified in material and personal time efforts. The learning outcome is a qualitative term represented by the application of learning output, whereby learning outputs are acquired qualifications or skills. The outcome as described in this paper is the application of qualification or skills in a work task. This can be quantified for example by reduction in human errors or required teach in time. Derived from existing strategies for increasing working productivity [5], the productivity of teaching and learning can be increased by applying a combination of the following principles. By increasing the learning intensity, for example through an increase of the user's ability to learn, a larger outcome is achieved with a static input. By rationalizing the learning process, i.e. achieving a larger outcome with less input, an increase in productivity can also be achieved. Learning rationalization can be achieved through scale effects of ICT based learning (Figure 3). Learning material is hereby made available to a multitude if users.

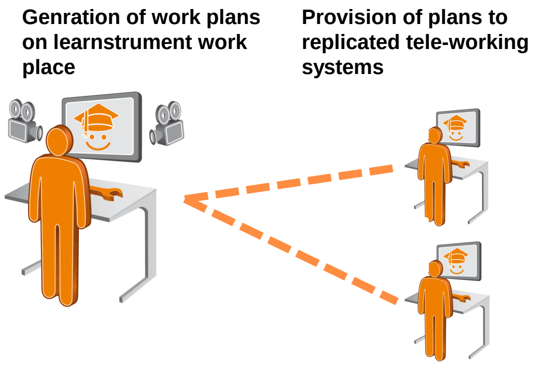


Figure 3: Scale effect of learnstrument application for tele-workplaces

2.3 User qualifications and skills

In order to derive necessary design requirements for learnstruments, a functional analysis for assembly systems in terms of ability to mediate their functionality has been developed and is described in Section 3. The functionality of the system as equipment is to facilitate to execution of the working task; working plans fulfill the mediation function in this case. The functionality of the system as a learnstrument, however, is to provide the user with the required skills and qualifications for its proper usage. The functional analysis approach to mediation functions attempts to develop a system in such a way that users of various skill and qualification levels are able to use it correctly, for example error free assembly of the product as well as the ability to operate systems with similar functionality within a minimum time for learning the system. The focus lies clearly on the latter, as the correct operation is therein implied.

In an initial step, the proposed concept applies a user qualification and training competence portfolio to classify the required and available skills and knowledge.

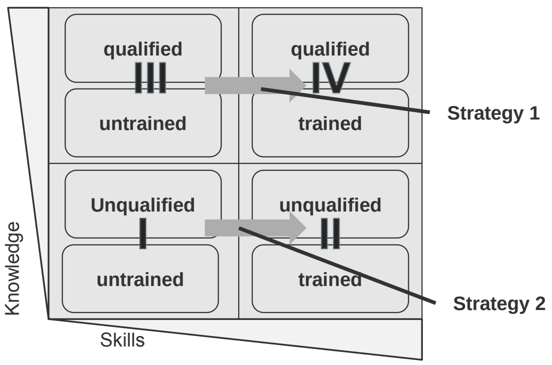


Figure 4: Knowledge/Skill portfolio

The portfolio shown in Figure 4 divides the user into four quadrants according to possessed knowledge and skills. Knowledge is hereby understood as information gained in a qualification process and skills as the ability to apply this knowledge though training or similar experience as described in Section 2.

The following strategies can be derived through classification of the envisioned user of a learnstrument for manual assembly within the portfolio:

- Strategy 1: Hands on training of manual assembly work place design and work plan generation for qualified users (III)
- Strategy 2: Hands on training of assembly processes with error feedback for untrained users (I)

By integrating mediation functions which signal the user about possible errors, e.g. improper selection of torque, as opposed to merely excluding the possibility of improper usage, cp. error free design, the user may be able to properly operate further systems without such error avoidance elements. In the best case, he or she will be able to identify such error reduction potential and provide insight for improvement potential.

3 METHOD OF DESIGN FOR LEARNSTRUMENTS

Existing design approaches have been analyzed for their applicability in developing and evaluating assembly system concepts which fulfill the following criteria for learnstruments: *identification of knowledge requirements for task completion according to user qualification, representation of mediation functions from system to user, identification of principle solutions for mediation functions within the system and evaluation of principle solution according to learning productivity*. An excerpt is shown in Table 1, illustrating those methods and design tasks which will be described within the next sections. Characteristic is the advantage of methods for the development of interactive (expert) systems and dialogs such as CommonKADS [8] or usability analysis [9]. Such methods are applicable due to their explicit analysis of information transfer, a key element of the learning process.

Table 1: Method evaluation for learnstrument design [8][9][10][11]

	Usability analysis	Knowledge Analysis	Morphological Matrix	Functional Structure	FMEA	MAKSI
Requirement Analysis	◕	◑	○	○	◔	◔
Functional Analysis	◑	◑	○	◕	◔	◔
Concept Generation	○	○	◑	◑	◔	◔
Concept Evaluation	◔	○	○	◔	◔	◕

○	meets no requirements	◔	meets some requirements
◑	meets many requirements	◕	meets most requirements

An excerpt of a design process is shown with modifications for mediation based design to illustrate the necessary consideration resulting from the portfolio strategies:

Planning and clarifying tasks – Definition of required knowledge and skills, Definition of knowledge and skills to be mediated by the system

Conceptual Design – Integration of mediation functions within the system, Evaluate learning principals for achieving the functions

The embodiment design will not be discussed.

3.1 Defining knowledge and skill requirements

Although primarily focusing on the use context of software applications and dialogs, the use context of physical interaction with a manual assembly system can also be analyzed according to the international standard for usability of dialog systems [9].

The use context analysis of the working task is supplemented with a task analysis according to the knowledge engineering approach, CommonKADS [8]. This method provides a knowledge centered tasks analysis, from which required knowledge for mediation within the learnstrument can be derived from an analysis of the working task.

The example in Table 2 shows the knowledge item *Screw Settlement Behavior according to the CommonKADS task analysis*. Of particular interest is the tacit and experienced based character of this knowledge, i.e. it is not represented visually or verbally and it is generally not quantified. The available form should be addressed in the functional requirements of the system. Following guidelines can be derived: *make experience based knowledge explicit*, *supplement tacit knowledge with explanatory learning material* and *decrease knowledge limitations*.

Table 2: Knowledge Item Analysis [8]

Task Model	**Knowledge Item Worksheet TM-2**	
NAME	Screw Settlement Behavior	
POSSESSED BY	Assembler	
USED IN TASK	Hub Casing assembly	
Nature of the Knowledge		**Bottleneck**
Experience based	X	X
Tacit, hard to transfer	X	X
Form of the Knowledge		
Mind	X	X
Availability of knowledge		
Limitations in access	X	X
Limitations in quality	X	X
Limitations in form	X	X

3.2 Defining mediation functions

The functional structure according to [10] is comprised out of the solution independent functions required in the system and their respective flows of material, energy and signals. Of particular interest for the analysis are the signal flows. In a first stage, the required and desired knowledge assets are reduced to singular signal flows and prescribed to existing functions, this is shown here for the introduction of the signal *noise* to the *Working System* function. For the remaining signal flows, knowledge transfer functions are introduced as shown here with the introduction of the function *Interpret signals*. Based on the knowledge analysis described in table 2, torque wrenches could be applied directly within the working systems. By additionally introducing a visual representation of applied torque through the learning system, the worker receives training in interpreting the natural signal *tension*.

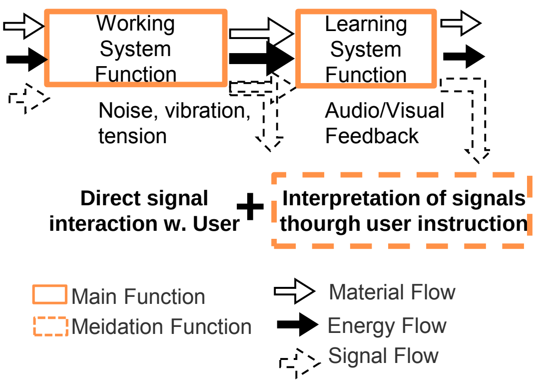


Figure 5: Functional structure of generic work place system with mediation functions

3.3 Evaluation of Mediation solutions

Empirical examination from Jeske et. al. have shown a differentiation in the teach-in time for manual assembly tasks in combination with written, graphical and animated working plans for engineers and non-engineers. [11]. Freiling et. al have shown, through an empirical study using the "Lernförderlichkeitsinventar" (LFI Learnability Inventory), that participative and cooperative working structures have a positive effect on the learnability of the working system [12]. A direct correlation to economic success could not, however be derived.

A short description of the learning process itself will be provided, in order to justify the application of the method MAKSI for evaluating solutions for the described mediation functions.

Learning occurs though perception and processing of inputs from the surrounding environment. The process most commonly ends with the reception of additional fact or information. The perception occurs both though thought and reflection as well as through emotion. For example the user sees a visual assembly instruction and derives a required sub sequence through reflection. He or she may also associate depicted elements emotionally and derive a subjective feeling for the task importance.

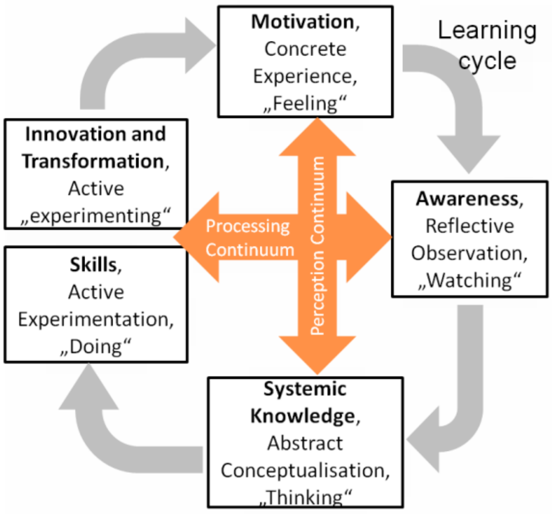


Figure 6: Learning cycle with perception and processing continuum

This process is represented in the perception continuum as depicted in Figure 6.

Additionally, processing of the learning material occurs in a two dimensional area in which the passive and active learning situation face each other. Passive learning situations contain observing and reflective elements which serve to create awareness for an input. The other extremity of the continuum builds the conscious acting in a learning situation. Tasks are completed (doing) and skills are acquired. Well known processes are adapted, in order to perform experimental system observations and to validate hypothesis (Figure 6).

Learning processes can go through all or some of the elements. A large learning productivity can be achieved when the user sequentially goes through all elements. The goal of the learnstrument design must therefore be to provide the user with the opportunity to develop a positive feeling for the learning input, to observe a situation, which he then thinks about, imitates a process and actively tries out concept he has in mind in order to again receive a positive learning impulse. This results in the design guideline: *Utilization of multiple learning methods and integration of learning methods which promote* ***M****otivation,* ***A****wareness,* ***K****nowledge,* ***S****kills and* ***I****nnovation in working/learning task design.*

Conceptual solutions for mediation specific functions can now examined for their applicability to the user and the use task according to the MAKSI scheme.

4 INCREASING ERROR TOLERANCE

A practical focus lies on increasing error tolerance and learnability of work place system thus increasing the productivity of teaching on the job.

By designing the system in such a way that no errors can occur, the user is not made explicitly aware of his or her false operation. This can cause errors when using a system without similar error avoidance elements, but more importantly, the user cannot reflect upon the design consideration that has been made to avoid a possible common error.

This can be avoided by identifying possible human error and prescribing avoidance, containment and identification measures which involve system feedback to the user [9]. Textual, visual or animated feedback can be integrated, providing the user with background information about the design principles which later can be used to make more accurate improvement suggestions in a participative environment. This concurs with the mediation oriented design principle: *Application of experimentation in work decision making.*

This approach combines error avoidance with error tolerance and is perceived as a guideline for mediation oriented design: *Introduction of multi-media elements for error identification.*

5 CASE: LEARNSTRUMENT FOR MANUAL ASSEMBLY AND REPAIR

The described methods and concepts have been implemented in a series of prototypes for application in workplaces for manual bicycle assembly and repair. This section will highlight some results from analysis and implementation for the manual assembly of electrical bicycle hubs.

5.1 Working and learning environment

The manual assembly work place consists of the work equipment required to fulfill the production task of assembling the hub, a pose recognition system and a work planning and evaluating software [13]. The learning task in this case consists of learning and evaluating the proper assembly execution sequence.

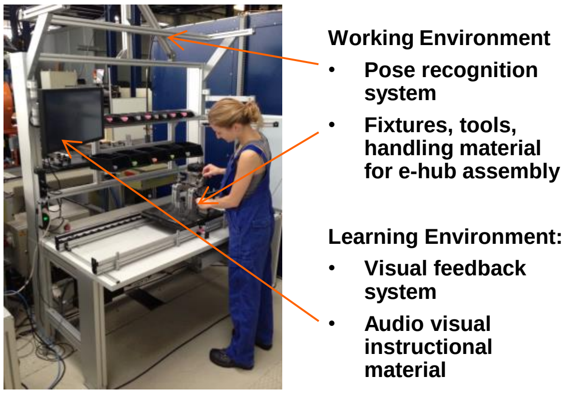


Figure 6: Learnstrument for manual assembly of electric hub

5.2 User classification

The learnstrument work place for manual assembly can be used by three types of users. The first user fulfills the tasks of planning the work place setup and work sequence. This task is supplemented with learning feedback in that the performed assembly tasks are characterized by the information system according to time measurement standards, allowing him or her to evaluate the chosen sequence. The second type of user is a worker who performs the assembly according to the derived instructions. This user may or may not work directly on the system which was taught in but may also perform the task on a replicated system which is provided with the electronic work plans (Figure 3). Finally, a perspective development of the system will allow the latter user to receive a feedback about his performance through a visual analysis of his work in comparison to the work plan. The first type of user is addressed in respect to Strategy I, the latter user in respect to strategy II as described in Section 2.3.

5.3 Concept evaluation and case conclusions

The selected solutions in this case promote various types of learning by both observation (i.e. Audio-Visual Instruction Material) and by active experimentation (i.e. alternating physical work sequence) and are therefore considered beneficial for increasing learning productivity through increased learning intensity.

Furthermore, the expert planners could increase the productivity of learning through scale effects of the repeated application of the working instructions in tele-working structures.

6 RÉSUMÉ AND OUTLOOK

The illustrated solutions for learnstruments for manual assembly work places promotes the increase of teaching and learning productivity required to address the future challenges of sustainable manufacturing. The fundamental object of observation is a combined learning and working environment. The main considerations in design are a learning centered development of the working tasks and equipment. The learnstruments embody both of these elements. The following strategies *Hands on training of manual assembly work place design for qualified users and Hands on training of assembly processes with error feedback for untrained users have* been derived and described. The following design principles have been identified for consideration in the system development:

- *Make experience based knowledge explicit, supplement tacit knowledge with explanatory learning material*
- *Integrate qualification and skill mediation functions within equipment design*
- *Utilize multiple learning methods in working/learning task design.*
- *Apply experimentation in work decision making.*
- *Introduce multi-media elements for error Identification.*

Continuing research will examine further applications and usability studies on the developed solutions will be performed for various target groups. Valuation of the concepts for application in industrial assembly systems will be examined within the Collaborative Research Centre *Sustainable Manufacturing – Shaping Global Value Creation*.

7 AKNOWLEDGEMENTS

The on-going research on Learnstruments in Value Creation Modules takes place within the German Science Foundation funded Collaborative Research Centre *CRC 1026 Sustainable Manufacturing – Shaping Global Value Creation*.

8 REFERENCES

[1] Abele, E., Reinhart, G., Zukunft der Produktion Herausforderungen, Forschungsfelder, Chancen. Carl Hanser Verlag, München, 2011, ISBN: 978-446-4595-8

[2] Seliger, G.; Reise, C.; McFarland, R.: Outcome-oriented Learning Environment for Sustainable Engineering Education, in: Proceedings 7th Global Conference on Sustainable Manufacturing, IIT Madras, IIS Madras, Chennai, pp. 91-98, 2009. ISBN: 978-81-904235-9-5

[3] M. Eisenberg, S. Heyer, C. Reise: Productivity In Engineering Education, in: Proceedings ICERI 2009, 16.-18. Nov. 2009, Madrid, Spanien, ISBN: 978-84-613-2953-3

[4] Reise, C.: Planung ingenieurwissenschaftlicher Qualifizierung mit Semantik-Web-Wissensbanken. In: Seliger, G. [Hrsg.]: Berichte aus dem Produktionstechnischen Zentrum Berlin, Fraunhofer-Verlag, Berlin, 2011, ISBN: 978-3-8396-0217-1

[5] Schlick., C., Bruder, R., Luczak, H.: Arbeitswissenschaft, 3. Auflage. Springer Verlag, Berlin Heidelberg. 2010.

[6] Metternich, J., Abele, E., Tisch, M.: Current activities and future challenges of the Process Learning Factory CIP. In: 3rd Conference on Learning Factories, May 7th 2013, Technische Universität München. 2013.

[7] M. Geyer, C. Reise, F. Manav, N. Schwenke, S. Böhm, G. Seliger: Open design for manufacturing – Best practice and future challenges; In: Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey, 2012, ISBN: 978-605-63463-1-6, Downloadable under: www.gcsm.eu

[8] Schreiber, G., et. al. Knowledge Engineering and Management: The CommonKADS Methodology. MIT Press, Cambridge, Massachusettes. 2000.

[9] DIN 9241-11: Anforderungen an die Gebrauchstauglichkeit. Beuth Verlag, Berlin, 1998.

[10] Pahl, G., Beitz. Pahl/Beitz Konstruktionslehre Methoden und Anwendung erfolgreicher Produktentwicklung. Springer Verlag, Berlin Heidelberg. 2010.

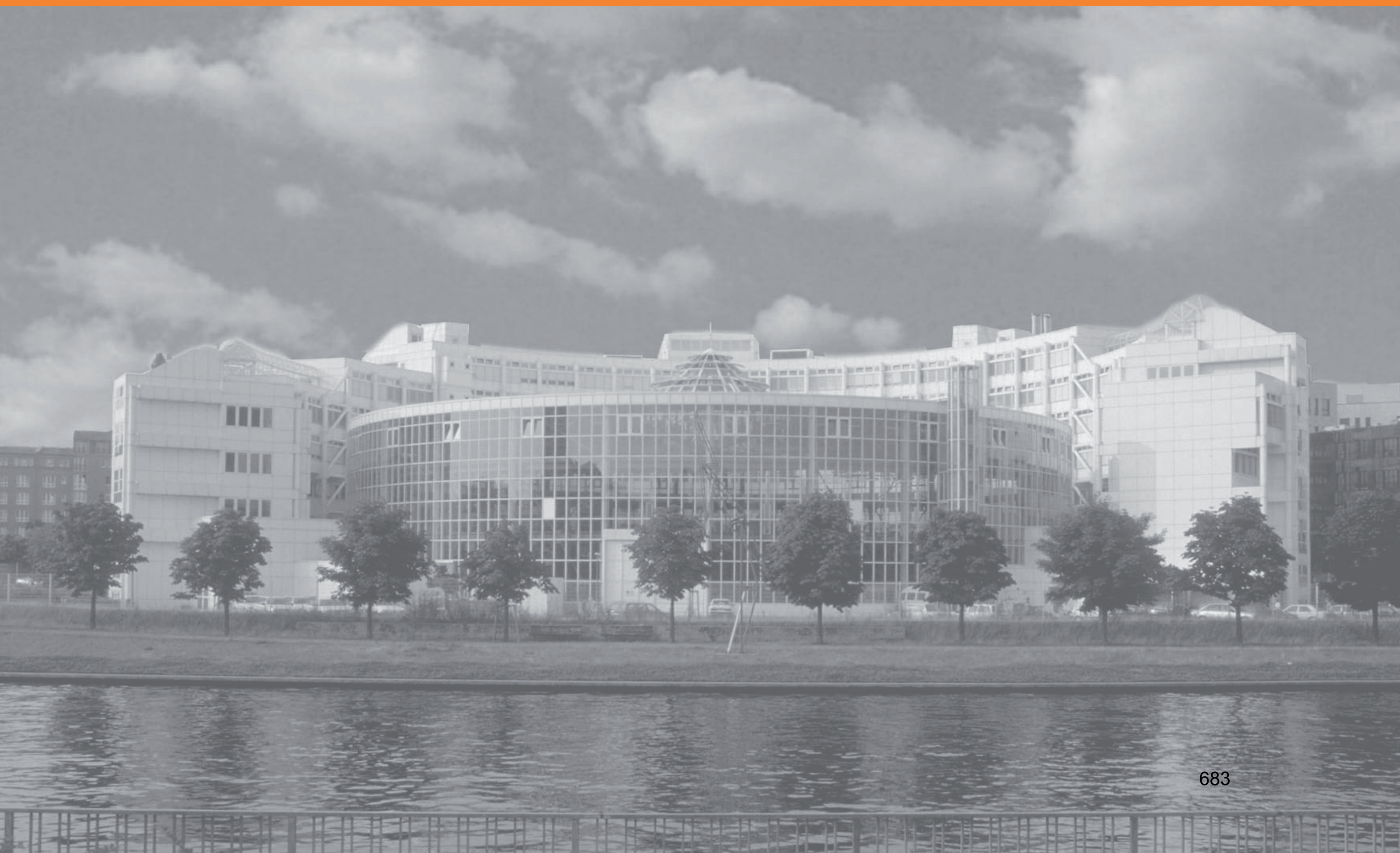
[11] DIN EN 60812: Analysetechniken für die Funktionsfähigkeit von Systemen – Verfahren für die Fehlzustandsart- und -auswirkungsanalyse (FMEA), Beuth Verlag, Berlin, 2006.

[11] Bornwasser, M., Zülch, G., Arbeitszeit - Zeitarbeit: Flexibilisierung der Arbeit als Antwort auf die Globalisierung. Springer Verlag, Berlin.2012.

[12] Freiling, E., et. al., Lernen durch Arbeit: Entwicklung eines Verfahrens zur Bestimmung der Lernmöglichkeiten am Arbeitsplatz. Waxmann Verlag, Berlin. 2006.

[13] Postawa, A.B., Kleinsorge, M., Krüger, J., and Seliger, G., Automated image based recognition of manual work steps in the remanufacturing of alternators, in Advances in Sustainable Manufacturing. 2011, Springer. p. 209-214.

Session 19
Energy Awareness



11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

19.1 A framework for a multiagent-based virtual enterprise with a microgrid energy market model

U. Aradag [1], B. Mert [1], G. Demirel [1], S. Uludag [2], H. O. Unver [1], S.Aradag [1]

[1] Department of Mechanical Engineering, TOBB University of Economics and Technology, Ankara, Turkey

[2] Department of Computer Engineering, TOBB University of Economics and Technology, Department of Computer Science, Engr and Phy., University of Michigan-Flint, Michigan, U.S.A

Abstract

Within the scope of the promising Smart Grid (SG) vision, the concept of microgrids is a key facilitator, especially in order to incorporate the distributed and renewable energy resources. In manufacturing, a Virtual Enterprise (VE) is a Web-based, virtual, and temporary consortium of companies with different core competencies to fulfill product orders during a specified period of time. In this paper, we are proposing a framework and an architecture of a Microgrid-based VE to diligently and intelligently manage energy consumption in the manufacturing process and to incorporate Distributed Energy Resources. We develop a conceptual framework for computing the energy requirement of a VE and come up with an energy pricing formulation in conjunction with a process and energy scheduling methodologies to reduce the Peak-to-Average ratio of energy usage. We utilize a Multi Agent System (MAS) in VE's clusters that is in full compliance with FIPA specifications.

Keywords:

Smart grid, virtual enterprise, renewable energy, Multiagent system

1 INTRODUCTION

Under the pressure of aging and increasingly ineffectual power grid, the notion of an enhanced and improved grid, under the generally used umbrella term of Smart Grid, is gaining growing interest and attention. The Smart Grid with the bidirectional flow of energy and information is an enabling and facilitating technology. SG is a grand vision for the new generation electric power system that benefits from increased use of Information and Communication Technology (ICT) [1], [2], [3]. SG proposes to adopt and implement the recent advances and improvements of ICT onto the grid. SG is poised to upgrade the largest man-made machine in the world for the future generations considering sustainability, efficiency, reliability, security, and power quality. One of the crucial building blocks of the SG vision is microgrids [4], [5], [6], [7]. A microgrid brings about capabilities to incorporate control and monitoring techniques to the low voltage distribution network so as to facilitate conventional and renewable energy resources, energy storage and intentional islanding from the main grid and contingency-based isolation. Microgrid has mainly been studied for residential areas within the past few years. The concept of microgrids in a manufacturing domain has received little attention, such as in [8]. The potential benefits of the concept of SG, especially by means of microgrid, appear to be profound. Yet, systematic integration of microgrids has not been tapped into to analyze and evaluate its full scale of merit in the manufacturing.

A collaborative approach is the best way for Small and Medium-sized Enterprises (SMEs) to exploit business opportunities more effectively. In this regard, a Virtual Enterprise (VE) is a collaboration network among multiple SMEs to reach business goals by sharing their capabilities using information, communications, collaboration and management technologies [9]. A VE is generally based around the collaboration among the SMEs before and through the job that is going to be realized. VE may be viewed as a key catalyzer for collaborative and flexible manufacturing so that SMEs may compete with larger enterprises [10]. The Multi Agent System (MAS) structure of the VE allows multiple functionalities and makes the addition of new SMEs as part of the VE system easier. Thus, VE increases the overall system versatility and reconfigurability.

In this paper, we provide a framework and an architecture for embedding energy requirements, as determined by the underlying Virtual Enterprise with Distributed Energy Resources, into the manufacturing process planning and scheduling. The energy infrastructure is modeled on top of the microgrid concept of the Smart Grid. A conceptual framework for computing the VE's energy requirement, an energy pricing formulation, and a process and energy scheduling methodologies to reduce the Peak-to-Average ratio of energy usage compose major parts of the overall system of our approach. We utilize a Multi Agent System (MAS) Energy Market in VE's clusters that is in full compliance with the Foundation for Intelligent Physical Agents (FIPA) specifications. To the best of our knowledge, ours is the first framework and architecture proposed in the literature that combines a microgrid energy market model on top of the recently developed VE-based manufacturing paradigm using an MAS infrastructure [9]. The Model consists of different agents that are responsible to fulfill the business functions that are needed by a VE to operate

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions

efficiently. The VE structure is an effective way of collaboration for SMEs to produce more complex products that they cannot produce by themselves otherwise. SMEs benefit more from the VE by getting hooked up with an Energy Market that will provide additional advantages as detailed in Section IV. The market is constructed upon auctions. MAS is used to cope with the distributed nature of the process and the microgrid system is used to integrate DERs easily into the system at the distribution level.

The rest of the paper is organized as follows: Section II provides the background on microgrids, MAS, and VE together with the related work. In Section III, we elaborate on our approach in determining the energy requirement of a VE. Energy Pricing Model for renewable sources is formulated and incorporated into our holistic system as part of the discussions in Section V. The overall energy market model, based on the preceding sections, is provided in Section IV. Finally, Section VI wraps up our approach with concluding remarks.

2 BACKGROUND AND RELATED WORK

2.1 Microgrid

With the bidirectional information and power flow provided by the Smart Grid, many new ideas are being proposed to augment and improve the current grid. One such extension is the concept of microgrid [4], [5], [6], [7]. A microgrid is a low voltage distribution network that is enhanced with Distributed Generation (DG), Combined Heat and Power (CHP), an energy storage subsystem, and/or a degree of autonomy to operate in intentional or accidental islanding mode. DG component of the microgrid might contain conventional as well as renewable sources. Microturbines, fuel cells, photovoltaic panels, wind turbines are some of the examples of the DG in the microgrid. The main benefits [6], [11] are improved reliability, integration of the distributed resources, isolation of power disturbances, and improving load and supply balance.

2.2 Multi-Agent System (MAS)

Artificial Intelligence has been applied to many real life applications, such as autonomous robots, Unarmed Aerial Vehicles (UAV), computer games, agent-based software development technologies [12], etc.

An entity that reacts to the changes in its environment through a reasoning process is referred to as an agent [13]. In this context, an agent can be a hardware, i.e a circuit breaker that acts upon the changes in the power grid, or a software which may be a virtual chess player, or even a human. Any hardware or software component may fall under the definition of an agent based on their goals and autonomy [14].

Multi-Agent System (MAS) is based on computational agents interacting and communicating with each other through a network [15]. Similar to other software development methodologies, MAS makes use of the divide-and-conquer mechanism. MAS is used to tackle complex problems. Each agent evaluates data gathered from the surrounding environment into its body and responds appropriately to push the whole system towards its goals [16].

MAS in manufacturing offers a dynamic, reliable and agile mechanism to enable adaptation to changes in the system with a faster response time in order to reduce cost and increase productivity [15].

The span of MAS application areas in power engineering includes diagnostics, condition monitoring, power system restoration, market simulation, network control and automation [17]. Along the same lines, MAS fits nicely to microgrids due to its flexibility and autonomy.

Expected and incipient proliferation of microgrid systems increases the need for an interoperable platform to facilitate as seamless integration as possible among different architectures and implementations [18]. Foundation for Intelligent Physical Agents (FIPA) standards and protocols have become important players to enable interoperability in this respect. The goal of FIPA is to promote agent-based technology and interoperability of its standards with other technologies [19].

Figure 1 shows the MAS development architecture of this paper which is based on the proposal in [18].

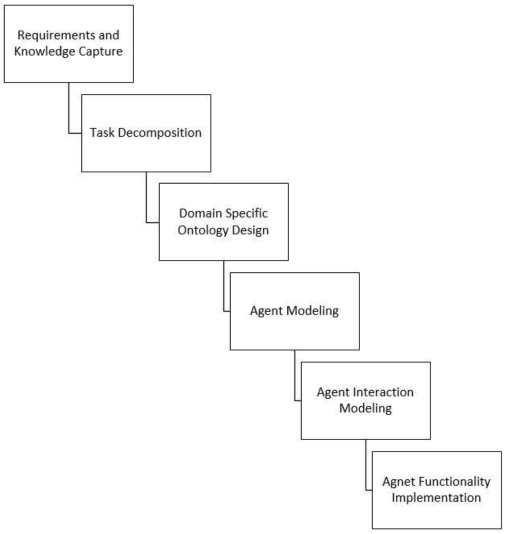


Figure 1: Agent Design Methodology proposed in [18].

Another work, built on top of the aforementioned architecture, is reported in [20] that proposes an Energy Management System for a microgrid-based Eco-Industrial Park. However, the proposal in [20] does not consider a VE infrastructure, unlike what we propose in this paper.

2.3 Virtual Enterprise

Virtual Enterprise (VE) consists of various SMEs with different characteristics that have to be combined in order to work together in a collaborative environment, thereby leading to a synergistic relationship of overlapping characteristics with MASs [21]. Agile manufacturing targets reconfigurable structures in order to respond to the demands of a dynamic and unpredictable market for a productive cooperation. VE embeds distributed independent enterprises with various core competencies [10]. An MAS-based VE can be used to develop different aspects of manufacturing systems, such as process planning and scheduling, supply chain management, etc.

An example MAS-based VE system as proposed in [9] includes the following agents: Customer agent, Task decomposer agent, Collaborative design agent, SME pool agent, Environmental performance management agent, Enterprise agent, Process planning and scheduling agent, Logistics management agent, Quality management agent:

Customer Agent (CA) is the agent facing the customer and collecting information regarding customer requirements.

Task Decomposer Agent (TDA) decomposes downstream production process into tasks.

Collaborative Design Agent (CDA) takes customer requirements and turns them into engineering specifications and enables collaboration between SMEs in the design processes:

SME Pool Agent (SPA) is the responsible agent from the SME registration and elimination to the VE

Environmental Performance Management Agent acts as an intermediary to reduce the ecological footprint. The responsibility of this agent is to benchmark and rank SMEs in the pool regarding their sustainability measures Enterprise Agent is responsible for the VE itself and operate in connection with the VE management subsystem.

Process Planning and Scheduling Agent (PPSA) is responsible for generating detailed process plans and routing data for the components that will be manufactured.

Logistic Management Agent manages the logistics be-tween SMEs located in the VE and responsible from the final assembly.

Quality Management Agent is responsible for the quality control and inspection of the parts manufactured in SMEs.

Four major stages of a VE are depicted in Figure 2 as opportunity capture, VE creation, VE operation and VE dissolution.

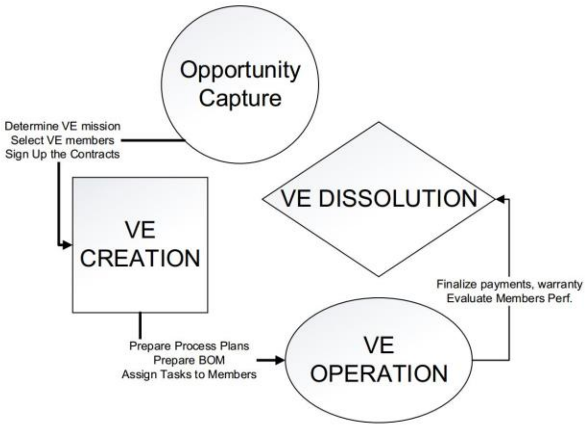


Figure 2: Virtual Enterprise Stages [9].

3 DETERMINING VE ENERGY REQUIREMENT

As indicated earlier, our MAS-based VE framework is based on [9]. The most relevant agent for the energy requirement determination of a VE is the Process Planning and Scheduling Agent (PPSA), which is responsible for generating and scheduling detailed process plans of the VE.

PPSA gathers the process plans of individual SMEs and combines them into a single large scale job plan that is represented by an hourly Gannt chart. In order to illustrate the process, below, we are using a real-life example to produce a Francis Turbine blade design and production process which can be accomplished on a VE with different SME capabilities.

The process starts with the receipt of the head and discharge values from the customer, and they will be used in the pre-design of the runner blades. The customer supplies the existing head and discharge values for a river that the hydro turbine will be used for. These pre-designs will be used for generating the solid model of the blades in a CAD program with various detailed processes. The first process will be accomplished in SME1, as shown in Figure 3. The solid model of the runner blades will be sent to SME2, as shown in Figure 4, for CAM process design and production. The output of SME2 will be the manufactured blades themselves, separately. The quality inspections will also be made in SME2 and the blades satisfying the quality specifications will be sent to SME3, see Figure 5. SME3 will assemble these blades into a turbine runner by connecting them with the auxiliary parts, two metal circular plates named hub and shroud. Therefore, the assembly phase of the VE will also be completed in SME3 and the VE will dissolve.

SME1	DAYS				
CFD-Analysis	■	■			
Solid Modeling			■	■	■

Figure 3: The process plan of SME 1.

SME2	DAYS				
NC Code Generation	■				
5 axis blade profiling		■	■	■	■
Q.C. compliant with IEC 60193					■

Figure 4: The process plan of SME 2.

SME3	DAYS				
Turning of hub and shroud	■	■			
Assembly of runner			■	■	■

Figure 5: The process plan of SME 3.

The process plans of the three SMEs are different from each other and concurrent. The combined schedule of SMEs will be formed as the scheduled plan of the VE itself, as given Figure 6. Note that the figures just show the process plan in the resolution of days. The actual VE process plan will have a granularity of hours.

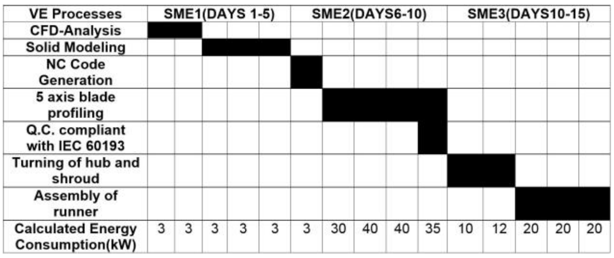


Figure 6: The final process plan of VE.

Once the process plan of the VE is generated, the next step is to determine the energy needed to carry it out. Computing the energy requirement of every single SME in the VE and then combining them would give us the total needed energy. The theoretical energy that will be used for one SME is the Product Embodied Energy (PEE) which is the result of the production activities and can be calculated by relating the energy consumed by the manufacturing processes, handling and environment maintenance [22]. In the early development phases such as the Solid Modeling and Computational Fluid Dynamics phases, energy consumption is based on basically the computer power consumed. Equation 1 represents this computation:

$$E_{Prod} = \sum_i E_{Process,i} + \sum_j E_{Handling,j} + \sum_k E_{Indirect,k} \quad (1)$$

where Eprocess is the energy consumed in the manufacturing processes, i is the part feature number that is being manufactured, Ehandling is the energy consumed by the automated material handling equipment such as robots and conveyors, j is the material handling activity number, Eindirect is the allocated indirect energy consumed by the services to maintain the environment for production activities of the part and k is the source for the indirect energy.

The energy requirement of every SME can be theoretically determined by the given formula above and the charts, such as Figures 3, 4 and 5 will be formed in an hourly manner for every single SME and the formula will be modified to fit the theoretical energy requirement calculation of a VE using the energy for each SME, E_{SME} and the transportation energy, $E_{Transport.}$ as;

$$E_{VE} = \sum_i E_{SME} + \sum_j E_{Transport} \quad (2)$$

The total energy required for the job that is going to be made on a VE will be formed by the PPSA agent and will be ready to be scheduled by the scheduling agent as part of the whole VE process by means of the underlying Energy Market (EM) model to be discussed in Section IV. The energy requirement chart of the VE is then sent to the Energy Scheduling Agent (ESA). ESA will be responsible for scheduling the energy required by the VE, by considering the properties of the VE. Scheduling will be realized with the objective function of minimizing, or at least reducing, the Peak-to-Average Ratio (PAR) so that a smoother or flattened energy consumption is achieved. One significant goal of Smart Grid microgrids is the minimization of the PAR [23]. As the PAR goes down, the seller agents located in the Energy Market will supply energy easier and with smaller peak energy supply losses. That means smaller losses. So, as the seller losses decrease, it will provide cheaper energy for the VE and VE will purchase energy for less. In addition, smaller energy losses mean a smaller impact on the environment, which is a basic goal of a VE [9]. Thus, both the VE itself and the sellers in the market will benefit from the given situation. The scheduled energy requirement of the VE will then be sent to the buyer agent of the VE that will be created on the energy market. This agent is explained in details in the next section.

4 ENERGY MARKET MODEL

In this section, we provide a synopsis of the proposed energy market model and framework.

4.1 MAS Methodology

The energy market is based on a Multi Agent Systems (MAS). MAS is composed of agents as intelligent autonomous entities which should exhibit the following characteristics [14]:

Pro-Activeness: Intelligent agents are goal-directed entities. They should be able to change their behavior dynamically based on their goals. This means that an agent should look for multiple solutions and adapt to the changes in its environment to fulfill its goals.

Reactivity: An intelligent agent should also react to the changes in its environment.

Social Ability: Intelligent agents could communicate with each other with respect to an ontology. This communication is more complex than a simple data transfer as it involves negotiation and taking initiative.

With the collaborative work and communications among intelligent agents, energy market will be formed to serve as a clearing house for the VE. In this clearing house, similar to the grid's bid-based, security-constrained economic dispatch with locational pricing model with day-ahead and hour-ahead pricing [24], energy market contracts will be sealed between participants using similar mechanisms. Participants will be buyer agents and seller agents. Buyer agents are classified as follows:

1) Large Enterprise: The word "Large" describes the energy need of the enterprise. Hence any agent that belongs to enterprises which consumes electrical energy larger than some predefined threshold is considered as Large Enterprise Buyer Agent. Special terms and deals may be provided to them during the negotiation phase.

2) VE Buyer : VE Agent will aggregate the total electrical energy needs of its participants and represent them in the energy market. After purchasing the energy, it will be assigned to each participant with respect to their demands.

3) SME Buyer : The remaining buyers that do not belong to any VE are categorized under this notation.

4.2 FIPA

The Foundation for Intelligent Physical Agents (FIPA) is an organization which defines standards for MAS and agent communications to achieve interoperability. FIPA defines Agent Communication Language (ACL) as the standard language for the agent communications [19]. Since agent communications is based on message transfer between agents, FIPA ACL standard predefines the structure of passing message between agents. Every FIPA ACL message should contain performative parameter which defines the communicative act.

4.3 JADE Platform

For development environment, Java Agent Development Environment (JADE) [25] will be used. JADE can also be considered as a runtime environment for FIPA-compliant agents. JADE platform is a distributed platform which is composed of agent containers that can be distributed over the network. The platform that is hosting agents can be split into multiple hosts and can act as a single platform. One of these containers, the main container, is the first container that is launched. It hosts two special agents to provide management services for agents and yellow pages services: Agent Management System (AMS) and Directory Facilitator (DF) respectively.

In accordance with the FIPA specifications, JADE platform provides a Message Transport Service (MTS) to exchange messages between and within the platforms. JADE also implements the standard Message Transport Protocols (MTPs) for providing interoperability between different platforms as defined by FIPA. Messaging between the agents within the same (local) platform is provided by Internal Message Trans-port Protocol (IMTP). One of the most important reasons for choosing JADE as the development framework is its consistency with FIPA standards with its built-in features, such as AMS, DF and MTS. Agent development and testing can be realized using JADE based on FIPA standards.

4.4 Market Methodology

In this study, we mainly focus on auction methodologies which are defined by FIPA standards. These are FIPA English Auction Interaction Protocol and FIPA Dutch Auction Interaction Protocol. With these interaction protocols, agents negotiate with each other for accomplishing their goals. In the energy market, negotiation cycle goes between buyer agents and seller agents. FIPA English Auction Interaction Protocol is presented in [26] to explain the negotiation in the market methodology. In the English auction interaction protocol, initiator, seller agents in this case, starts the auction and informs the participants, buyer agents. Initiator sends Call for Proposal (CFP) performative for proposing the price of the good and waits for the accept proposal performative. Each time, at least one participant, accepts the price, initiator gradually increases the price. With that negotiation method, participants try to find the market price of the good that they are selling. Auction continues until no participants accept the price. In that case, initiator sells the good with the last price that is accepted.

Another interaction protocol that is provided by FIPA is Dutch Auction Interaction Protocol [27]. In that case initiator, buyer agents, starts the auction by sending CFP to the participants, seller agents. Participants send their prices as their proposals. In this interaction protocol, sellers start from a price which is higher than the market price and the price is gradually decreased until one of the buyers accepts it. First-come first-served principle is employed in this protocol, i.e. the first buyer who accepts the current price on negotiation will buy the good. Usually there is a reserve price for the good which is the lower limit for the good. Auction terminates if no buyers accept the reserve price.

Negotiation frequency will be one hour to implement hour-ahead energy market. Grid prices will be announced to the energy market before the negotiation cycle starts. Market Controller Agent (MCA) will aggregate the total demand and total available power before each cycle and decide the interaction protocol according to these aggregated demand and supply. The interaction decision is based on the following methodology:

$$\text{Protocol} = \begin{cases} \text{Dutch Auction}, & if \sum D > \sum S \\ \text{English Auction}, & if \sum D < \sum S, \end{cases}$$

where D is the demand and S is the supply for energy. In this methodology, the intention is to favor the lesser side. If the supply side is greater than the hourly demand side, then the sellers will start the auction with English Auction Protocol in which the energy price starts from the minimum reserve price and increases the price. In this case since the demand side is less than the supply side, energy contracts are expected to be settled at lower prices with respect to the other case. When the demand side is greater than the supply side, Dutch Auction Protocol will be applied with the intention that seller may sell their energy for higher prices.

Energy market model including the SMES to show the overall work presented in this paper is shown in Fig. 7. On the user side, SMEs are located where triangles represent SMEs whose agents are SME Agents, larger triangles represent Large Enterprise Buyer and circle represents VE Agent with its SME Agents inside.

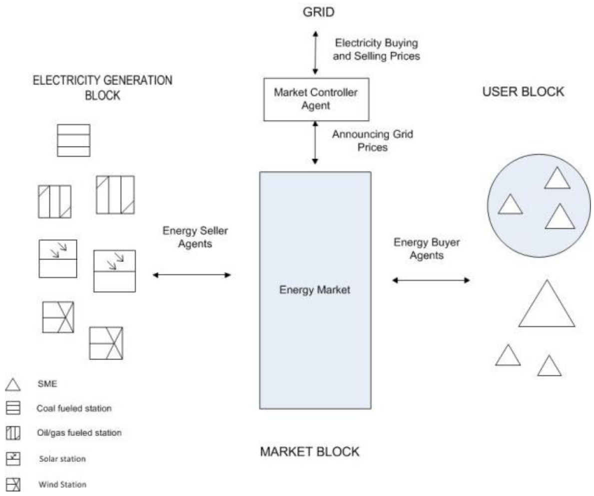


Figure 7: Energy Market Model.

After the negotiation period is ended, each agreed contract between buyer and seller is stored in the Market's database for future references. After all the processes ended for the next-hour energy market, all the buyer and seller agents are terminated and they are recreated before each negotiation cycle with updated information from their users.

5 ENERGY PRICING MODEL

In the literature, the cost of renewable energy usually consists of four components, as shown in Figure 8: capital costs, fuel costs, cost of decommissioning, operation and maintenance (O&M) costs [28].

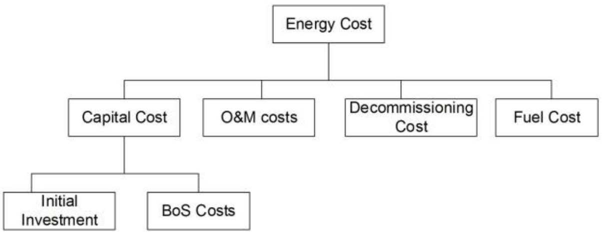


Figure 8: Cost components of renewable energy cost model.

For most renewable energy systems, the fuel costs are assumed to be zero, due mostly to government subsidy. According to the Dutch Auction Interaction Protocol, ESAs propose bids considering the time-dependent energy cost function which starts from a maximum price and works its way downward until it reaches minimum price with profit.

A general form of energy price function is given below:

$$Pr_{i,t} = Pg_t - \left(\left\{Pg_t - Pm_{i,t}\right\} * \lambda_T\right) \quad (3)$$

where $Pr_{i,t}$ is the energy price of i_{th} renewable module at time t, Pg_t is the price of the main grid which is obtained by the Microgrid Control Agent (MCA) hourly and is announced to the electricity market, $Pm_{i,t}$ is the minimum energy price of the i^{th} solar module at time t, and finally, time dependent coefficient is λ_T .

$$\lambda_T = \frac{Current\ time - Initial\ Time}{Deadline - Initial\ Time} = \frac{Tc - Ti}{Td - Ti} \quad (4)$$

For estimating the bids price ESAs propose, the maximum and minimum prices should be determined primarily. The maximum price equals to the main grid price. Besides, minimum cost is combination of capital cost, decommissioning cost, O&M costs and the support of government. The capital cost of PV systems include the cost of PV modules, the connection cost of modules to form arrays, the array support structure costs, the cost of cabling, charge regulators, inverters and storage batteries costs, etc. [28]. All these variables can be assumed as payback cost and the Balance of System (BoS) costs [29]. Payback cost can be computed using:

$$A_{i,t} = P_{i,t} * \frac{i*(1+i)^N}{(1+i)^N - 1} \quad (5)$$

where $P_{i,t}$ is initial cost of i_{th} renewable at time t, i is the interest rate and N is the payback time period in years. The capital cost is sum of payback cost ($A_{i,t}$) and BoS costs ($B_{i,t}$):

$$C_{i,t} = A_{i,t} + B_{i,t} \quad (6)$$

Substituting $A_{i,t}$ from Equation 5 into Equation 6, we get:

$$C_{i,t} = \left[P_{i,t} * \frac{i*(1+i)^N}{(1+i)^N - 1}\right] + B_{i,t} \quad (7)$$

After finding the capital cost the minimum price can be written as:

$$Pm_{i,t} = \left[C_{i,t} + D_{i,t} + O_{i,t} - \left(E_{i,t} * Ps\right)\right] * k_{i,j} \quad (8)$$

where $k_{i,j}$ is the percentage profit of i^{th} solar module for j^{th} buyer type (SMEs, large scale buyers and VE buyers), $D_{i,t}$ is the decommissioning cost of i^{th} solar module at hour t, $E_{i,t}$ is the energy (kW) that i^{th} solar module produced at hour t, P_s is the price per kWh government subsidy. The minimum price can be rewritten as follows:

$$Pm_{i,t} = \left\{\left[P_{i,t} * \frac{i*(1+i)^N}{(1+i)^N - 1}\right] + B_{i,t} + D_{i,t} + O_{i,t} - \left[E_{i,t} * Ps\right]\right\} * k_{i,j}$$

(9)

or Equation 3 can be expressed more explicitly by substituting Equation 9 into Equation 3 as:

$$Pr_{i,t} = Pg_{i,t} - \left(\left\{Pg_{i,t} - \left\{\left[P_{i,t} * \frac{i*(1+i)^N}{(1+i)^N - 1}\right] + B_{i,t} + D_{i,t} + O_{i,t} - \left[E_{i,t} * Ps\right]\right\} * k_{i,j}\right\} * \lambda_T\right)$$

(10)

6 CONCLUSION

In this work, a framework of an architecture is proposed for a Microgrid-based Virtual Enterprise to intelligently manage energy consumption in collaborative design and manufacturing processes involving several SMEs. Distributed Energy Resources (DERs) are thereby incorporated into to the system by means of the microgrid concept; one of the crucial constituent parts of the Smart Grid. The framework proposed is conceptual and used for computing the energy requirement of a VE. We also come up with an energy pricing formulation in conjunction with a process and energy scheduling methodologies to reduce the Peak-to-Average ratio of energy usage. A Multi Agent System (MAS) is utilized in VE's clusters that is in full compliance with the Foundation for Intelligent Physical Agents (FIPA) specifications. To the best of our knowledge, ours is the first framework and architecture proposed in the literature that combines a microgrid energy market model on top of the recently developed VE-based manufacturing paradigm.

The future work includes the implementation of the conceptual methodology developed in this paper for the collaborative design and manufacturing planning of hydro turbine blades assuming every single part of the turbine design and manufacturing as the work of a single SME. We are planning to study the impact of different energy package sizes, which is the smallest value of the energy that would be traded in the auctions. Its outcome should give us clues in terms of the required energy versus optimum package size correlations. Another dimension of an extension for our work is an aggregation scheme of the supply-side of the energy market by means of a virtual power plant concept [30]. We would like to evaluate pros and cons of such a supply-side consolidation in conjunction with our approach as outlined in this paper.

7 ACKNOWLEDGMENTS

This work is supported by Turkish Ministry of Development and TOBB University of Economics and Technology, financially.

8 REFERENCES

[1] NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0 Smartgrid Interoperability panel (SGIP), 2012.

[2] Final Report of the CEN/CENELAC/ETSI Joint Working Group on Standards for Smart Grids, 2011.

[3] Smartgrid Standardization Roadmap, IEC Strategic Group 3, 2010.

[4] Lasseter, R., 2002, Microgrids, IEEE Power Engineering Society Winter Meeting, 1:305-308.

[5] Lopes, J., Moreira, C., Madureira, A., 2006, Defining Control Strategies for Microgrids Islanded Operation, IEEE Transactions on Power Systems, 21/2: 916-924.

[6] Kroposki, B., Pink, C., Basso, T., DeBlasio, R., 2007, Microgrid standards and technology development, IEEE Power Engineering Society General Meeting, IEEE, 1-4.

[7] Vaccaro, A., Popov, M., Villacci, D., Terzija, V., 2011, An integrated framework for smart microgrids modeling, monitoring, control, communication, and verification, Proceedings of the IEEE, 99/1: 119 –132.

[8] Arinez, J., Biller, S., 2010, Integration requirements for manufacturing-based energy management systems, Innovative Smart Grid Technologies (ISGT), 1-6.

[9] Sadigh, B., L., Unver, H. O., Kılıc, S. E., 2012, Design of a multiagent based virtual enterprise framework for sustainable production, Virtual and Networked Organizations, Emergent Technologies and Tools, Springer, 186–195.

[10] Oprea, M., 2003, Coordination in an agent-based virtual enterprise, Studies in Informatics and control, 12/3: 215–226.

[11] IEEE guide for design, operation, and integration of distributed resource island systems with electric power systems," IEEE Std 1547.4-2011, 1 –54.

[12] Shoham, Y., Leyton-Brown, K, 2008, Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations, Cambridge University Press, Cambridge, MA.

[13] Hoek, W., Wooldridge, M. ,2008, Chapter 24 Multi-agent systems, Handbook of Knowledge Representation, Elsevier,3: 887 – 928.

[14] Wooldridge, M., 2008, An introduction to multiagent systems. Wiley.

[15] Unver, H. Ö., Sadigh, B. L., 2011, An Agent-Based Operational Virtual Enterprise Framework enabled by RFID. Handbook of Research on Mobility and Computing: Evolving Technologies and Ubiquitous Impacts,41.

[16] Monostori, L, Vancza, J., Kumara, S. R., 2006, Agent-based systems for manufacturing, CIRP Annals-Manufacturing Technology, 55/2:697-720.

[17] McArthur, S., Davidson, E., Catterson, V., Dimeas, A., Hatziargyriou, N., Ponci, F., Funabashi, T., 2007, Multi-agent systems for power engineering applications part i: Concepts, approaches, and technical challenges, IEEE Transactions on Power Systems, 22/ 4: 1743 –1752.

[18] McArthur, S., Davidson, E., Catterson, V., Dimeas, A., Hatziargyriou, N., Ponci, F., Funabashi, T., 2007, Multi-agent systems for power engineering applications part ii: Technologies, standards, and tools for building multi-agent systems, IEEE Transactions on Power Systems, 22/ 4: 1753 -1759.

[19] Foundation for Intelligent Physical Agents (FIPA). 2007

[20] Mert, B., Aradag, U., Uludag, S., Unver, H. O., 2013, An architecture for a microgrid-based eco industrial park using a multi-agent system, IEEE International Conference in Power Engineering, Energy and Electrical Drives (POWERENG), To appear.

[21] Shen, W. et al., 1999 Agent-based systems for intelligent manufacturing: A state-of-the-art survey." International Journal in Knowledge and Information Systems, 1:129–156.

[22]Unver, H.O., Uluer, M. U., Altin, A., Tascioglu, Y., Kilic, S.E., 2012, An eco-improvement methodology for reduction of product embodied energy in discrete manufacturing, Springer, 405–410.

[23]Hossain, E., Han, Z., Poor, H., 2012, Smart Grid Communications and Networking, ser. Smart Grid Communications and Networking. Cambridge University Press.

[24] Hogan, W., 2002, Electricity market restructuring: Reforms of reforms, Journal of Regulatory Economics, 21/ 1:103–132.

[25] Bellifemine, F., Caire,G., Greenwood, D., 2007, Developing Multi-Agent Systems with JADE, Wiley

[26] Foundation for Intelligent Physical Agents (FIPA) English Auction Interaction Protocol, 2007.

[27] Foundation for Intelligent Physical Agents (FIPA) Dutch Auction Interaction Protocol, 2007.

[28] Boyle, G., 1997, Renewable energy: power for a sustainable future. Taylor& Francis.

[29] Future for Renewable Energy Chapter 2: Future Research and Development in Photovoltaics. James &James Press.

[30] Pudjianto, D.,Ramsay, C., Strbac, G., 2007, Virtual power plant and system integration of distributed energy resources, Renewable power generation, 1/1:10–16.

19.2 Stochastic optimization method to schedule production steps according to volatile energy price

S. Emec[1], M. Kuschke[2], F. W. Huber[1], R. Stephan[3], K. Strunz[2], G. Seliger[1]
[1]Institute of Machine Tools and Factory Management, Berlin Institute of Technology, Germany
[2]Sustainable Electric Networks and Sources of Energy, Berlin Institute of Technology, Germany
[3]Konrad-Zuse-Institute Berlin, Germany

Abstract
Manufacturing systems are one of the main consumers of electrical energy worldwide. Inaccurate demand side prediction and time dependent renewable power generation can cause volatile energy prices in short term energy trading. Future manufacturing systems can benefit from volatile energy prices by managing their demand. This affects the profitability and also has a positive effect on CO_2-emissions. Leveraging this potential requires scheduling of production steps based on order situation, electrical energy demand of each machine, and day-ahead electricity market prices. A stochastic optimization method for the scheduling of production machines with specific processing times and energy consumption has been developed and implemented as a software prototype. The optimization method is validated for eight production machines as a part of a production line to shift load to off-peak hours when electricity prices are lower.

Keywords:
Manufacturing Systems, Energy Markets, Demand-Side Management, Optimization, Product-Service Systems

1 INTRODUCTION

Volatile and increasing prices of energy resources become a key factor in global competition. Companies are forced to use the progressive flexibility offered by manufacturing systems and integrate sustainable strategies through rescheduling production steps to resource- and energy-economical time.

In the last decade, the European manufacturing industry has witnessed an increase in electricity costs of 43% and the German industry an increase of 120% [1]. According to the prognosis of the European Commission, these costs will increase by another 23% by 2020 [2]. In Europe, electrical energy is still predominantly produced from non-renewable resources. The costs for these non-resources resources increased even more during that period. For example, the nominal European non-renewable primary energy resources costs increased in the last decade by oil 240% for petroleum, 207% for natural gas, and 185% for coal [3]. At the same time, the world manufacturing energy consumption is projected to increase by 44% from 2006 to 2030 [4].

Inaccurate demand side prediction and the higher percentage of renewable energy increases the uncertainty of energy supply because of fluctuating in-feeds and prediction errors. For more resource efficiency and effectiveness, consumption and generation of electrical energy need to take place at the same time. This leads to short-term trading of electrical energy. Time-dependent demand and generation of energy causes rapidly changing prices. However, a reliable forecasting and cost model for factory-wide electrical energy consumption hardly exists. Taking into account the degrees of freedom coming from the adaptation of electrical energy demand to volatile prices, time-flexible operations in production lines can become more profitable and can help to better integrate renewable resources to the power grid and reduce the CO_2-footprint.

In this paper, different scheduling strategies based on a model for cylinder head production line in the automotive industry are developed. The model relies on power measurement data of a typical production line. It is shown by simulation, how the production line can be scheduled by considering the order situations and automatically aggregated electrical energy demand of each machine. Thereby, the scheduling strategies are investigated with regard to the costs. Taking into account the electrical energy prices of the European Energy Exchange (EEX) spot market, an optimization based on the cost target function is implemented. The economic benefit is illustrated and the potential ecological benefit is discussed.

2 MOTIVATION

Limited resources, striving for economic and socio-political independence of the European Union inevitably lead to sustainable manufacturing. Sustainability Engineering is about exploiting the dynamics of fair competition by processes of knowledge creation and innovation in order to achieve sustainable global living conditions. One way to achieve this goal consists of substituting non-renewable resources with renewable resources. The economical challenge hereby is a resource-saving product-service design creating competitive products [5].

As presented in Figure 1, 89% of the primary energy consumption in Germany in 2011 still originates from non-renewable primary energy resources. Only 11% of the primary energy is from renewable resources helping to reduce the CO_2 emissions. After energy conversion and processing of raw materials, only 65% of the primary energy remains for final consumption. A percentage of 22% of the energy converted is directly available as electrical energy, which is 14% of the primary energy consumption. From the final electrical energy consumption 22% is generated by renewables. About 870PJ, approximately 46% of the electrical energy, was traded on the market as day-ahead and intra-day electrical energy to the consumer´s demand in 2011 [6].

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

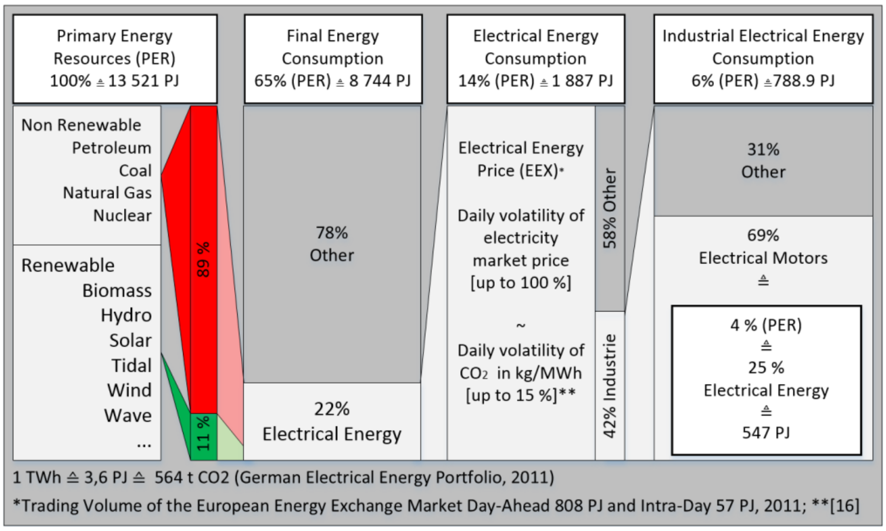


Figure 1: Quantitative assessment for German energy conversion in primary resources shares with loses in transformation.

Depending on the electrical energy generation portfolio, the CO_2 emissions per MWh generated change. Thereby, a part of 58% is consumed by commerce, public institutions, private households, and others, whereas 42% of the electrical energy is consumed by industry. It also means that 6% of the primary energy is consumed by industry for electrical energy needs. Most of the electrical energy consumed by industry is converted into mechanical energy by electrical motors. This is one fourth of the overall generated electrical energy in Germany. Chiotellis and Grismajer show an approach for real-time analysis of electrical power, based on data stream analysis [7]. Taking this approach into account, it is theoretically possible to identify value adding processes and calculation of production planning relevant indicators out of power measurements in real time.

An application for this approach could be grid stability and short term trading of electrical energy. Since the electrical energy is more and more generated by fluctuating renewable energy sources, an increasing importance for power grid stability accrues for the loads. The benefits of managing this significant percentage of energy consumed by industrial electrical motors are twofold: more efficient grid integration for renewable energies can be reached, the company's energy costs can be reduced and the consumed electrical energy could be theoretically scheduled to a CO_2 neutral time.

2.1 Problem Description

In this paper, a result-oriented service is developed aligning the production schedule and order situation to the spot market prices for electrical energy.

The electrical energy demand of a production machine, line, and factory or across multiple factories in a neighbourhood is flexible within the production constraints. If the production line does not operate at full capacity, then there is an opportunity to shift production steps over a day. Smart meters can provide real-time electricity prices from the market to the factory. If this information is utilized effectively by customers via in-process monitoring of electrical power in relation to operation steps of the production machine, then the electrical energy costs can be reduced. This can be done by scheduling the load to off-peak hours when the prices are low. Thus, the CO_2-footprint can be reduced. While it is relatively easy to consider the day-ahead prices in the scheduling process of a single machine, the complexity increases dramatically when considering the production line. A production line consisting of only a few machines presents much more constraints and production necessary data from different sources. In addition, the scheduling strategy needs to be flexible to react on changing constraints. It is also important to develop a generic model which can be easily adapted to other production lines and multiple objective functions.

To achieve this goal a generic discrete-time mixed integer linear programming (MILP) model is developed and implemented in the Advanced Interactive Multidimensional Modeling System (AIMMS). The input data is given by the power measurements of the production line and the EEX spot market prices.

2.2 State of the Art

In the United States minimum energy efficiency standards can trace their origins to the mid-1970s. At that time, the first programs implemented aimed to change both the level and the time of electricity demand among the customers [8]. This method is defined as demand-side management (DSM), also known as energy demand management, referring to the management of time-flexible loads. On the one side, it can be applied for shifting peak loads to reduce the demand if there is little energy generated by renewable sources. On the other side, DSM can also be useful for valley filling, for example to increase the electrical load at night consuming the energy produced by renewable sources.

In order to realize DSM, advanced metering infrastructure (AMI) has to be installed on the consumer side. These smart meters measure the electricity consumption, condition and convert the data signals as well as have computational tasks and communicate with the superior hierarchy data management unit. Besides DSM, the AMI additionally offers the energy suppliers the possibility to generate a better load forecast for day-ahead planning by changing load information. This is of high interest, since it helps to improve the system's efficiency by also reducing the need for ancillary services such as frequency regulation services. With regard to industrial consumers, all time-flexible production processes can take part in DSM. Implementing DSM, incentives for adapting the demand according to the renewable energy generation are to be given to the consumers. This can be done by linking the electricity price to the amount of energy generated by renewable sources such that the consumers benefit from reduced prices in times with high generation. To that aim, different pricing models can be found in literature [9]. One simple pricing model for example can be realized by offering an on-peak and an off-peak price. Another approach, which is implemented in this work, is to connect the demand to the real-time electrical energy market prices. This approach assumes that the electrical energy for the production line is fully obtained at the EEX spot market.

The economic potential for DSM of industrial processes in developed countries has been recognized by numerous institutions and authors as Mitra [10], Paulus [11], Graus [12]. These publications deal with various processes, mainly from the chemical industry, where the consumption of electricity depends on different unit operations: grinding (cement, paper pulp production), compression (air separation), electrolysis (chloralkali, aluminum) and drying (paper production).

The energy profiles of all manufacturing equipment can be combined in cumulative load profiles for different factory levels e.g., energy demand for a machine, a process chain, or the whole plant. Moreover Dornfeld and Vijayaraghavan show in 2010 that the analysis of the energy profile with a different sample rate allows choosing a best energy usage strategy for a particular manufacturing tool or a whole process [13]. Vijayaragavan and Dornfeld proposed a software-based approach, which allows automated energy reasoning and support decision making based on the complex event processing (CEP) and rules engines (RE) techniques in order to automate monitoring and analysis of energy consumption in manufacturing systems [13]. This approach was further developed by Chiotellis and Grismajer for real-time analysis of electrical power, based on data stream analysis and event-driven system and implemented as a software application [7]. The approach allows aggregating all scheduling relevant productions data out of measured power streams. This reduces the number of needed information sources for the proposed model into measured power data and daily energy price from the EEX market. The following method uses the real-time analysis of electrical power as input adapter, which is described by Chiotellis and Grismajer for state detection, to indicate the electrical energy consumption and the process duration for each machine in the production line.

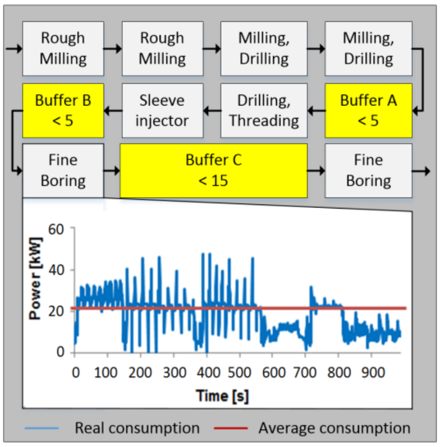


Figure 2: Production line model and power stream.

3 PRODUCTION LINE MODEL

This section describes the production line model. Information is given on the required production line data and the necessary simplifications of the real data. The prototype developed is evaluated by scheduling an existing production line in an automotive industry.

The layout of the production line as well as one example for the power consumption of the included production machines is shown in Figure 2. Every production machine consumes a different amount of electrical energy over time and process. The diagram demonstrates the power consumption over the processing duration as well as the average energy consumption.

3.1 Machine States

Each type of electrically driven production equipment has various operating states that can be characterised by energy consumption and duration. The energy consumption of production machine is the sum of the energy consumption of their components. In order to execute production tasks, a sub-set of the components is activated and depends on the predefined process. The needed mechanical energy will convert directly from the electrical energy and thus consumes energy according to its operating profile. Weinert provides illustrative examples and modelling framework for operating states [14]. The production machine operation states can be identified from the metered power profile [7]. Considering the electrical energy consumption three relevant machine states for energy based scheduling can be identified:

- **Idle:** lowest energy consumption ~ 0,1% - 1% constant base power - no value creation
- **Waiting:** higher energy consumption ~ 10% - 40%, machine is waiting to produce - no value creation
- **Processing:** highest energy consumption ~100%, product, process specific energy profile - value creation

3.2 Scheduling Horizon

The prototype shall calculate the optimal production schedule for the next day. Therefore the scheduling horizon is 1 day ≙ 24 hours. The electrical power consumption data is streamed with 1 Hz frequency from each production machine and is given as kW/s. This data is logged on the embedded industrial PC. Each processing step and duration of machines is automatically extracted from the meter [15]. The extracted process duration is given in seconds. A time slot length of one second would lead to 86400 time slots per day. So the prototype would have 86400 time slots in which every machine could be in “Processing”, “Waiting” or “Idle” state. Additionally the constraints have to be fulfilled for every time slot. This would result in an extensive computational time.

To avoid an extensive computational time the time slot lengths should be as long as possible. This leads to set the greatest common divisor (gcd) as time slot length determined from scheduling horizon of 24 hours, the electrical energy price interval of 1 hour and all time durations of the “Processing” state. The time slot in this case is set of 300 seconds ≙ 5 minutes. This leads to process durations between one and three time slots and a scheduling horizon of 288 time slots (≙ 24 hours).

4 IMPLEMENTATION

In this model a MIP formulation is chosen. The reason is that the prototype will be more generic and will be able adjust more quickly to scheduling problems with different target function, constraints, number of machines, machine configurations and electrical energy consumption.

Sets:	
M (index m)	Set of production machines
T (index t)	24 hour time horizon divided in 5 minute timeslots denoted by *t*
J (index j)	Set of jobs/orders
Binary matrix (variables):	
P_{jmt}	1 when job *j* on machine *m* at timeslot *t* is processing
W_{jmt}	1 when job *j* on machine *m* at timeslot *t* is in waiting state
I_{jmt}	1 when job *j* on machine *m* at timeslot *t* is in Idle state
X_{jmt}	1 when job *j* on machine *m* at timeslot *t* is starting
Parameters:	
pi_m	Consumption of the "Idle" state
pw_m	Consumption of the "Waiting" state
pp_m	Consumption of the "Producing" state
pu	Capacity limit - sum of all machines is limited to this value
d_m.	timeslots - each machine *m* has constant predefined process duration
ts	Earliest start time – no process can start before this timeslot
te	Latest end time – every process has to be finished before this timeslot
tc	Current timeslot ($ts < tc < te$)
b_m	Buffer opportunities after each production unit
c_t	Cost per kWh from the EEX market "€/kW per timeslot"
c_e	Total cost for the electrical energy over 24 hours
c_s	Simplified total cost for the electrical energy over 24 hours
c_c	Considered energy cost for the electrical energy of one day
o_m	Necessary time period for switch from waiting to idle

Table 1 : Relevant definitions.

4.1 Mathematical Model

The mathematical model includes the machine model and the constraints of operation of the machines as well as the overall production line. Special attention is given to a computational time-reduced model in the planning horizon.

Each machine *m* has to be in one of three consumption states: pi_m (consumption of the "Idle" state), pw_m (consumption of the "Waiting" state), pp_m (consumption of the "Producing" state). The energy consumption of the sum of all machines is limited to a value denoted by *pu* (capacity). Each machine *m* has a constant predefined process duration d_m. The scheduling intervals are set to 5 minutes slots. Thus, parameter d_m contains the required number of timeslots for processing. Each timeslot is specified by *t*, whereas *tc* is the current time. The planning horizon is bounded by two special settable timeslots: the earliest start time *ts* and the latest end time *te*. Outside these timeslots, the consumption state is set idle. The number of parts ordered is called jobs and denoted by *j*. The buffer opportunities following each machine in the production process are defined by b_m. The cost per kWh is extracted from the EEX spot market and converted to "€/kW per timeslot" which is saved in vector c_t. The time to switch to idle state for every machine is given in vector o_m.

The Costs Target Function: The total cost for the electrical energy over 24 hours results from the different machine states *(P, W, I)* multiplied by their power consumption *(pp, pw, pi)* and the electrical energy costs (*c*) at every time slot:

$$\sum_{\forall j,m,t} \begin{pmatrix} P_{jmt} * pp_m * c_t + W_{jmt} * pw_m * c_t \\ + I_{jmt} * pi_m * c_t \end{pmatrix} = c_e \qquad (1)$$

To reduce the computing time, the model considers only two machine states in the planning horizon: "Producing" and "Waiting". Outside of it, each machine is in "Idle" state. Since avoiding the relatively high energy consuming "Waiting" state is mandatory, the optimization result is analysed by a second procedure. This procedure changes the "Waiting" state to "Idle" state whenever "Waiting" is active for o_m (default is 15 minutes) number of timeslots or longer. This limitation ensures that no damage is induced by switching the production equipment off and on too often. The simplified total cost function is:

$$\sum_{\forall j,m,t} (P_{jmt} * pp_m * c_t + W_{jmt} * pw_m * c_t) = c_s \qquad (2)$$

The planning horizon includes two states from which one has to be applied to every timeslot. So W_{jmt} can be defined by P_{jmt} as W_{jmt}= 1 - P_{jmt} follows. This lead to the equation for the simplified total energy costs:

$$\sum_{\forall j,m,t} (P_{jmt} * pp_m * c_t + (1 - P_{jmt}) * pw_m * c_t) = c_s \qquad (3)$$

The last simplification is that instead of optimizing the producing time, it is much faster to schedule the start times of every job. The effect on the results will be minimal because the average process duration is 11 minutes and the price changes every 60 minutes. The considered energy cost is the target function:

$$\sum_{\forall j,m,t} (X_{jmt} * pp_m * c_t) = c_c \qquad (4)$$

The aim is to find the values of X_{jmt}, P_{jmt}, W_{jmt}, I_{jmt} minimizing the considered energy cost while fulfilling the following constraints.

Constraints: Constraints are equations and inequalities which reduce the set of possible results for the target function and the variables. In this prototype constraints are mathematically equivalent to the physical constraints given by the production line model. Every job *j* on a production unit *m* needs to be fulfilled before the end time. Fulfilment constraint:

$$\sum_{t=ts}^{te} X_{jmt} = 1 \,. \quad \forall\, (j,m) \qquad (5)$$

At every timeslot *t* the sum of energy consumption must not exceed the mandated capacity *pu*. Capacity constraint:

$$\sum_{\forall j,m} (W_{jmt} * pw_m + P_{jmts} * pp_m) \le pu \quad \forall\, t \qquad (6)$$

To start a new job on a production unit the previous job on this unit need to be finished. Ordering constraint:

$$(7) \quad \sum_{t=ts}^{tc} t * X_{j\,m\,t} + d_m \geq \sum_{t=ts}^{tc} t * X_{j+1\,m\,t} \quad \forall\,(j,m,tc)$$

Starting a new job on a production unit, the same job on the previous unit needs to be finished. Example: processing step 5 of job 10 can only start if the processing step 4 of job 10 is finished. Dependency constraint:

$$(8) \quad \sum_{t=ts}^{tc} t * X_{j\,m\,t} + d_m \geq \sum_{t=ts}^{tc} t * X_{j\,m+1\,t} \quad \forall\,(j,m,tc)$$

The storage opportunities of the processed parts after each production unit are limited. Consequently the number of jobs done by the previous machine minus the buffer b_m must not exceed the number of processed jobs on the next machine. Buffer constraint:

$$(9) \quad \sum_{t=ts}^{tc} X_{j\,m\,t} - b_m \leq \sum_{t=ts}^{tc-d_m} X_{j\,m+1\,t} \quad \forall\,(j,m,tc)$$

4.2 Program Architecture

The architecture of the prototype includes three parts, presented in figure 3. The necessary inputs are:

- **INPUT ADAPTER:** State detection out of measured power stream and calculation of energy per job [7].
- **Electrical cost per hour:** Daily electricity market price €/MWh for 24 hours.
- **Manual Input:** Number of orders, earliest/latest starting time and chosen strategy.

In the second part “program” the LP file is processed by the mathematical solver CPLEX to determine the ideal start time of each job on every production machine. Thus, the binary matrix X_{jmt} will be calculated. The ideal start time is given, if the first derivative of the target function (4) is equal to zero and second derivative greater than zero.

Next a procedure calculates the binary matrix. Followed by the optimization of the schedule through changing the “Waiting” states to “Idle” whenever is possible. The optimised production schedule is used to calculate the electrical energy costs for the production line. This cost in combination with exported version of the production schedule is categorised as the output part of the prototype.

4.3 Scheduling Strategies

The scheduling of the production steps according to the volatile energy prices is done through shifting the jobs in different manners. Shifting offers the possibility to start processes when the electrical energy price is low. Each strategy stands for a different way to generate the production schedule and requires further degrees of flexibility. The constraints limit the degree of freedom. Three main scheduling approaches are the basis of our investigations:

- **Without Shift:** Every job is fulfilled one after the other. Start time of the first job is fixed.
- **Block Shift:** Every job is fulfilled one after the other. The start time of the first job is flexible. First job need to be started within a variable timeframe.
- **Window Shift:** Every job can start at every time in the defined planning horizon.

Out of these scheduling approaches five scheduling strategies (S) were derived:

- **S0:** Equates the current state of the production scheduling plan. The electrical energy price is kept constant. (Without Shift)
- **S1:** Take into account volatile electrical energy prices from the EEX market. (Without Shift)
- **S2:** The start time of production blocks is flexible. Start time with the lowest energy costs is chosen. (Block Shift)
- **S3:** Every job is fulfilled one after other. (Window Shift)
- **S4:** The “Window Shift” gets shifted over the predefined flexible start time. The start time with the lowest energy costs is chosen. (Block Shift; Window Shift)
- **S5:** Every production machine starts with one unprocessed part from the day before in it. As a result every machine can start at the same time. (Block Shift, Window Shift)

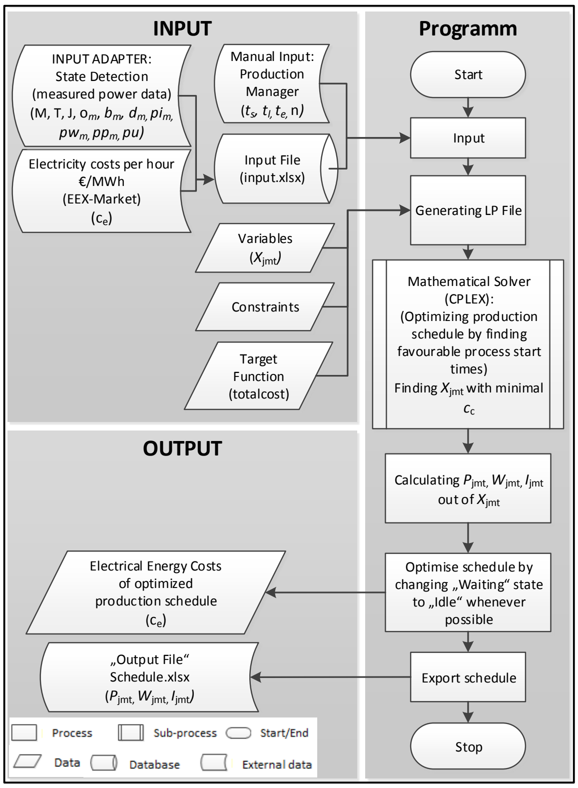


Figure 3: Program flowchart.

5 RESULTS

To demonstrate the potential of this method, 20 orders consisting of 8 production machines as a part of a production line are scheduled. The orders are equivalent to a typical day with a low workload or high maintenance activities. The strategies are tested for three different days. The daily base price for one MWh on the EEX market oscillates round 42€/MWh. The first day, 2nd May 2013 represents a low European Electricity Index (ELIX) Day Base (EDB) for a working day with 32,48€/MWh. The second day is the 25th Sep. 2012 with an EDB of 42.9 €/MWh and represents an average working day. The third day is 13th Feb. 2012 is a high EDB of 109 €/MWh.

The result is shown in figure 4. As mentioned before the first strategy S0 represents the electrical energy costs based on constant energy price of 0,12 €/kWh. Other strategies S1 – S5 schedule the production line according to the EEX Market. The savings for the first two days (low and average EDB) for all strategies are between 58% and 78.6% of the electrical energy costs compared to the current electrical energy costs. The third day (high EDB) strategies S2 - S5 provide savings between 3.2% and 32.3%. The strategies S1 would result in higher electrical energy costs between 19.4%. These outcome need to point out even if the EDB is 256% above the average all strategies which include shifting of processes lead to electrical energy costs savings. The results show that the flexibility of the production line is directly proportional to the cost and CO_2 savings. The most important saving factors are:

- **Flexibility:** Jobs with low shifting range have a low optimization potential. The flexibility is affected by the constraints and the capacity of the production line.
- **Consumption margin:** The main factor in reducing electricity costs is avoiding the non-value-adding machine states. If their electricity consumption is very low the benefit of avoiding them is also low.

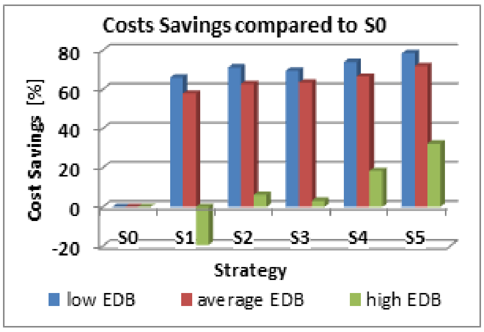


Figure 4: Normalize electricity cost savings.

6 SUMMARY AND OUTLOOK

A method for saving electrical energy costs by scheduling a production line according to the electricity market price has been developed and implemented. The input data for the model is mainly acquired from electrical power data and an interlinking to the EEX spot market. It was shown that depending on the scheduling strategy and the volatile electrical energy prices that the savings are up to 78.6% of the electrical energy costs. These savings correspond to 64.50€ and 34kg CO_2.

Future work includes a multi-criteria based optimization which will allow the minimization of the CO_2 emissions and the electrical energy costs. Additionally, the idle optimization should be included in the LP formulation. This has to be done by adding an additional variable.

7 ACKNOWLEDGMENTS

The present work has been funded by the European Union FP7 "Factories of the Future" research project "KAP: Knowledge, Awareness and Prediction". The authors would like to acknowledge the support and contributions of KAP industrial and academic partners in the development of this work.

8 REFERENCES

[1] Bundesministerium für Wirschaft und Technologie (BMWi): Energie in Deuschland – Trends und Hintergründe zur Energieversorung, 2013.

[2] European Commission - Directorate-General for Energy: EU energy trends to 2030 http://ec.europa.eu/energy/observatory/trends_2030/doc/trends_to_2030_update_2009.pdf, 2013.

[3] Andruleit, H., Babies, H. G., Meßner, J., Rehder, S., Schauer, M.,: Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen, Deutsche Rohstoffagentur (DERA), Hannover, ISSN: 2193–5319, 2011.

[4] Verl, A., Westkämper, E., Abele, E., Dietmair, A., Schlechtendahl, J., Friedrich, J., et al.: Architecture for Multilevel Monitoring and Control of Energy Consumption, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, pp. 347-352, 2011.

[5] Seliger, G.: Sustainability Engineering by Product-Service Systems, In: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, pp. 22-28, 2011.

[6] European Power Exchange EPEX SPOT, Day-Ahead (DE/AT) and Intra-Day (DE/AT) trade volume for 2011 http://www.epexspot.com.

[7] Chiotellis, S., Grismajer, M., Analysis of electrical power data streams in manufacturing, 19th CIRP International Conference on Life Cycle Engineering, Berkeley, pp. 533-538, 2012.

[8] Louhran, D. S., Kulick, J.: Demand-Side Management and Energy Efficiency in the United States, The Energy Journal Vol.25, No. 1, pp. 19-43, 2004.

[9] J. Ekanayake, K. Liyanage, J. Wu, A. Yokoyama, N. Jenkins. Smart Grid - Technology and Applications, Wiley, Chichester, UK, 2012.

[10] Mitra, S., Grossmann, I. E., Pinto, J.M., Arora, N.: Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes, Computers & Chemical Engineering, Volume 38, pp. 171-184, 2012.

[11] Paulus, M., Borggrefe, F.: The potential of demand-side management in energy-intensive industries for electricity markets in Germany, Applied Energy, Volume 88, Issue 2, pp. 432-441, 2011

[12] Graus, W., Worrell, E.: Methods for calculating CO2 intensity of power generation and consumption: A global perspective, Energy Policy, Volume 39, Issue 2, February 2011, pp. 613-627, 2011

[13] Dornfeld, D., Vijayaraghavan, A.: Automated energy monitoring of machine tools. CIRP Annals-Manufacturing Technology, Volume 59, pp. 21-24, 2010.

[14] Weinert, N.: Vorgehensweise für Planung und Betrieb energieeffizienter Produktionssysteme, Fraunhofer IRB, Stuttgart 2010.

[15] ICT-2010-10 Smart Factories: Knowledge, Awareness and Prediction of Man, Machine, Material and Method in Manufacturing, D1.3 – Specification of energy monitoring infrastructure, 2012.

[16] Grobmaier, T., Schröpel, V.: Forschungsstelle für Energiewirtschaft - Analyse des Zusammenhangs, September 2010, www.ffe.de (Access June 2013).

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

19.3 MEDA: Manufacturing Energy Demand Assessment method for future production planning and product development

M. Abramovici [1], A. Quezada [1], T. Schindler [1]

[1] Chair of IT in Mechanical Engineering, Ruhr-Universität Bochum, Germany

Abstract

Sustainability drivers such as competitive advantages through sustainable products, environmental regulations and social awareness motivate manufacturing companies to implement measures such as energy management systems, which require energy balancing of manufacturing processes. Unfortunately, current methods for energy demand assessment do not sufficiently meet industrial requirements. As a consequence, practical application of these methods in production planning and product development remains incomplete. This paper proposes a method focused on energy demand analysis of manufacturing processes. It is based on a combination of existing and self-developed assessment methods. Going beyond energy balancing, due to suitable KPIs, the method application provides feedback information not only to production planning but also to the development of future product generations. The method has been validated by the analysis of a gearwheel manufacturing process in a crane manufacturing company.

Keywords:

Energy efficiency, energy demand assessment, product lifecycle, manufacturing, product development

1 INTRODUCTION

1.1 Energy-efficient manufacturing processes – A key issue for sustainability

The increase of energy efficiency is a crucial issue that concerns all sustainability dimensions (social, economic and ecologic). The benefits of energy-efficient products involve all economy and society including the public sector, businesses, and private individuals. According to the International Energy Agency (IEA), an increase in energy-efficiency plays an equivalent role for climate protection as the sum of renewable energies and other environmentally friendly measures [1] [2].

The competitive advantage of a green image combined with a permanent increase in energy efficiency requirements stipulated by governmental policies, laws, and standards (norms, labels, guidelines, etc.) has become a considerable motivation for manufacturing companies to implement measures that improve the energy efficiency of their products over their entire lifecycle. One of the main requirements of finding energy-efficient measures is permanent energy-demand assessment of manufacturing processes. This kind of assessment not only provides important information for taking the right decisions not only during production planning but also for the development of future product generations [1] [2].

1.2 Goals

Unfortunately, there is a lack of simple methods for energy demand assessment, since current approaches are too general and their application in product development and production planning remains incomplete (cf. chapters 2 and 3). The goal of this paper is to provide a quick review of this problem and to present a solution: the MEDA method. The goal of this method is to support manufacturing companies in performing simple and rough energy demand assessments of internal manufacturing processes, especially energy-intensive processes such as metal heat treating. This analysis helps defining appropriate measures in future production planning and product development.

2 STATE OF THE ART OF METHODS AND TOOLS FOR ENERGY DEMAND ASSESSMENT

This chapter focuses on some of the most important methods and tools that support environmental assessment respectively energy balancing.

Life Cycle Assessment and Energy Balancing

The Life Cycle Assessment (LCA) framework provides general guidelines for environmental assessment and is described in the ISO 14040 series. Its application field is very large and includes manufacturing processes. The LCA framework and software represent today the most support for environmental assessment [1]. Energy balancing can be considered as a lean version of LCA [3]. Unfortunately, the LCA framework alone is neither specific nor detailed enough to substantiate the energy balancing of manufacturing processes [2].

Process chain analysis

The analysis of process chains is an important method for the description of operational processes in companies [4]. On the basis of a process chain analysis, all kinds of systems can be modeled in an abstract way and then analyzed by other methods e.g. energy flow and energy cost analyses [3] [4].

Cumulative Energy Demand

The VDI guideline 4600 describes the calculation of Cumulative Energy Demand (CED) for all kinds of products

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

and systems. The approach considers all product lifecycle stages including manufacturing processes [5].

Energy and Material Flow Analyses

This method is based on energy and material balance described in ISO 50001 [6]. In industrial practice, it is used at company, process, and product level. It considers three main questions: What is the input of the system? What is the output of the system? What happens between input and output? [7].

Energy value stream mapping

This method is used by enterprises to meet sustainability objectives. To comply with these objectives, energy value stream mapping is used. The basis of this method lies in the value stream mapping of business studies, which are mapped and adapted based on energy-relevant topics. To support this method, product optimization is envisaged, which will be planned in the value stream design phase [8].

Eco Integral

The use of business information systems can be highly important for a widespread use of environmental management tools, in order to integrate them. This is the main idea behind the "eco integral" project. An implementable reference model for use in different branches has been developed. The reference model has served as a development basis of integrated business information systems for environmental concerns [9].

Energy navigator

For this method, the property-driven design approach has been adapted to an energy-efficient design. By integrating energy efficiency aspects into target costing, energy design goals and costs can be monitored. Additionally, a system ontology is proposed to enable the integration of product models from different engineering disciplines and to provide data for the calculation of energy consumption. A software architecture (energy navigator) has been proposed for this method [10].

Further methods and tools

Further methods to support statements about the efficiency of products with regard to raw material usage, energy demand and product lifecycle are: the CO_2 footprint, the emission limit analysis the CML method, MIPS (Material Input per Service Unit) method, the EPS Enviro-accounting Method, the Pinch-Point Analysis, etc. These methods, however, are only partly suitable for manufacturing processes.

All of the methods briefly outlined above propose different approaches and solutions for eco- and energy balancing. Unfortunately, they show one major disadvantage: They do not provide sufficient information about how to substantiate specific method stages. In this context, the user has insufficient practical association or instructions, so that the following questions remain unanswered: What is the adequate way to measure energy consumption/expenditures? Which indicators are important? How does the user obtain the indicators? What must be done if there is no possibility to measure all necessary information?

Furthermore, most of these methods have to be general to make them applicable for many different issues. Another challenge is that, in most of the companies, the necessary know-how to generate such balances is spread across many employees. Quick results and optimizations are therefore not possible. A further challenge is that most of these methods require lots and in parts difficult-to-obtain data as input. Obtaining such indicators is entirely justified and reasonable, but for most companies that need quick results this kind of method is often not possible to achieve due to time and financial constraints. In addition to this, it is important for manufacturing companies to assess energy-related cost. The Life Cycle Costing (LCC) method is a rewarding solution for this kind of assessment [11].

To develop a feasible method that can be used in a model company, requirements have been defined that consider the limits of existing methods described above and try to comply with industry requirements.

3 INDUSTRIAL REQUIREMENTS FOR AN ENERGY DEMAND ASSESSMENT METHOD

This chapter defines the requirements for an adapted energy demand analysis method based on the theoretical pool of methods mentioned earlier. The important stages for the definition of requirements are the description and modeling of processes, the lifecycle inventory phase, and enabling IT-based feedback of information into product development. The requirements described in this chapter as well as the concept outlined in chapter 4 are to be considered in the manufacturing phase.

On that basis, the following requirements for an assessment method for energy demand of internal manufacturing processes have been defined. They are divided into general and specific requirements for the each individual stage.

General requirements

- Enable rough assessments through simplicity (the method must be simple and easy to use), and fast application (results must be achieved quickly).
- Transparent overview of results (simple and structured overview of results, also for management use).
- Manufacture process-specifically (The method must be adapted to the "manufacturing" lifecycle stage).
- Adaption to further lifecycle phases possible (Fast adaption to further lifecycle phases must be possible).
- Product development and manufacturing planning as target group.
- Energy demand, energy-related costs and global warming related emissions of internal processes must be quantifiable from the company's perspective.

Specific requirements for goals and system definition

- Product description (Solution for the product description and visualization must be proposed and developed respectively).

- Description of manufacturing process (Solutions for the description, modeling and visualization of manufacturing processes must be developed).
- Input and output of systems (must enable the identification and marking of most important input and outputs).
- Detail levels (The system must be visualized in different detail levels depending on the complexity of the balance).
- Selection of System boundaries (A selection of system boundaries must be available based on the modeled product and processes).

Specific requirements for assessment

- Selection of a reference value (A reference value depending on the collected data must be selected).
- Data research (Proposals for research possibilities for data must be shown, e.g. databases, ERP).
- Measurements (Proposals for possible measurements and possible difficulties when measuring).
- Calculation models (Proposals for the calculation and their influencing variables from data research and measurement must be generated).
- Indicators (Suitable indicators for the manufacturing phase must be proposed).
- Data visualization (Model visualization possibilities for the collected data must be shown, which allow a structured acquisition of data).
- Summary of collected data (All of the collected data must be visualized for the purpose of presentation e.g. in a table).
- The quality of the assessment must be quantifiable.

Specific requirements for result interpretation and definition of measures

- Identification of potential (Lifecycle inventory potentials must be identifiable by comparison of processes).
- Visualization of potential (Simple possibility to visualize potentials must be proposed).
- Support definition of improvement measures.

In compliance with the above requirements, manufacturing companies need a simple and rough method, as well as IT tools to perform energy demand assessments of their internal manufacturing processes.

4 THE MEDA METHOD

This chapter describes a method developed by the authors in collaboration with an industrial crane manufacturing company. The Manufacturing Energy Demand Assessment (MEDA) method considers the requirements presented in chapter 3.

4.1 General method description – main differences to other assessment methods

The MEDA method provides detailed instructions to its users on how to model manufacturing processes and calculate their energy demand. The structure of the method has a lot in common with standardized assessment methods and frameworks (cf. chapter 2). Due to the specific requirements of manufacturing companies (cf. chapter 3), however, the MEDA method shows the following important differences:

Focus on company perspective and internal manufacturing processes

Most existing approaches are based on the entire lifecycle. (cf. chapter 2). In order to enable comparisons among different phases, the results of energy demand are provided 'primary energy equivalent'. In practice, however, for financial reasons, manufacturing companies are also interested in the energy consumption and energy-related cost of their internal processes or, in other words, what they have to pay for energy consumption (cf. chapter 3). For this reason, the MEDA method focuses on the company's perspective and internal manufacturing processes. Therefore, the method proposes specific indicators such as energy cost for company and energy demand of final respectively use energy (cf. 4.2). This also facilitates the analysis of internal energy losses.

Main method phases

The method has three main phases: Phase 1 is called '**goals and system definition'**. Analogous to an integration of the LCA stages inventory analysis' and 'impact assessment', the second phase is called '**inventory and energy demand assessment'**. The last phase is analogous to the LCA stage 'interpretation' and is designated as '**results analysis and definition of improvement measures'**.

4.2 Phase 1: Goals and system definition

Similar to the 'goal and scope definition' phase of the ISO 14040 LCA framework, the main goal of this phase is to define the limits of the **manufacturing process** that is to be analyzed (system boundary). However, different from ISO 14040 and other approaches, the MEDA method already predefines:

- the 'degree of detail' of the assessment, and
- the method for modeling processes that are to be analyzed.

Detailing levels of data

The method proposes a classification of process data according to four detailing levels (cf. Figure 1). The first level concerns all manufacturing processes of parts, components, or of an entire product. The second level subsumes the main manufacturing sub-processes. The third level applies to unit manufacturing processes. The fourth and last level concerns the single activities (steps) of the unit manufacturing process. To allow simple and rough energy demand assessments (cf. chapter 3), data from single activities of unit manufacturing processes are not considered for assessment. Minimum detailing level requires data from at least the main manufacturing processes.

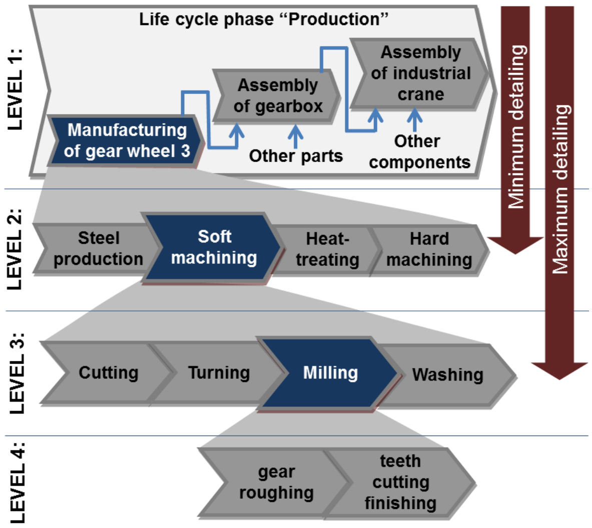


Figure 1: Process levels for data collection – example of a gear wheel manufacturing process for ind. crane gearbox.

Process modeling method

The method considers the requirements of chapter 3 and is based on a process chain analysis approach (cf. chapter 2). It also follows the rules of the classification shown in Figure 1. As shown in Figure 2, inputs/outputs are graphically represented for each process and level. The main goals of this modeling are:

- Define the limits of the assessment (system boundary)
- Define data (input/outputs) needed for the inventory and energy demand assessment (cf. 4.3)
- Define data relationship of processes from different levels
- Facilitate comprehension via a graphic representation

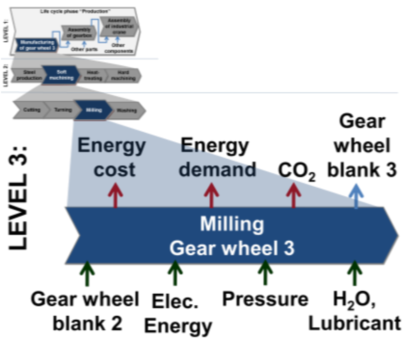


Figure 2: Example of input/output modeling of a milling process of a gear wheel.

The data collected and included in process models contains information needed for the calculation of method-specific indicators (cf.4.3). If necessary, models defined in this phase can be completed or modified in the subsequent phases (e.g. by adding more precise information about inputs/outputs). Alternative models with alternative processes can also be defined to allow comparisons.

4.3 Phase 2: Inventory and energy demand assessment

The goal of this phase is to collect data and calculate method-specific indicators of the analyzed process. Basically, the values are to be calculated for a process on level 1 according to the classification in 4.2. To achieve this, respective values must be calculated for processes on levels 2 and 3. The method-specific indicators are:

- **Use energy-demand [KWh $_{\text{use energy}}$ / product unit]**

This indicator represents the amount of energy required for a product manufacturing process inside the company.

- **Final energy-cost [Euro / product unit]**

This indicator represents the energy-cost for a product manufacturing process inside the company.

- **CO_2 direct emissions [Kg CO2 $_{\text{equivalent}}$ / product unit]**

This indicator represents the amount of CO_2-equivalent direct emissions from a product manufacturing process inside the company (only emissions related to global warming) [12].

Data quality degree

As data from different sources can have different reliability, a quality coefficient has been introduced to measure and weigh the reliability of each data source. The method proposes a classification of data on three levels:

- Coefficient 3 for high quality data: Data from direct measurements and/or internal reliable sources (e.g. ERP Systems) and specific to the analyzed process.
- Coefficient 2 for medium quality data: Data from external sources, which are specific to the analyzed process, e.g. supplier databases.
- Coefficient 1 for low quality data: Data from open source databases and/or not specific to the analyzed process.

The mean value of input and output data coefficients defines the 'Data quality degree' of the entire assessment. However, weighing factors can be defined for data that is particularly relevant to the company.

As shown in Figure 1, the manufacturing of a gear wheel for an industrial crane gearbox includes a heat treating process. Tables 1 and 2 below illustrate the calculation of the indicators for the analysis of such a process. These results are part of the case study described in chapter 5.

	Energy demand			Energy cost		
Input / output	Values per part	Data quality coef.	Data source	Values per part	Data quality coef.	Data source
INPUT						
Gear wheel blank 3	10,50 kg	3	ERP-System	10,50 kg	3	ERP-System
Natural gas	39,13 kWh use energy	3	Measure	0,05 €/kWh = 1,95 €	3	ERP-System
Electrical energy	2,10 kWh use energy	3	Measure	0,15 €/kWh = 0,31 €	3	ERP-System
OUTPUT						
Gear wheel blank 4	10,50 kg	3	ERP-System	10,50 kg	3	ERP-System
Total /part	41,23 kWh use energy	3		2,26 €	3	

Table 1: Example of energy demand and energy cost calculation for a gear wheel heat treating process.

Input / output	Values per part	Data quality coefficient	Data source
INPUT			
Gear wheel blank 3	10,50 kg	3	ERP-System
Propane	0,08 m^3	3	
Methanol	1,14 $*10^{-3}$ m^3	3	
Natural gas	39,13 kWh use energy	3	Measure
OUTPUT			
Gear wheel blank 4	10,50 kg	3	ERP-System
CO_2	4,62 kg	3	Measure
N_2O	6 10^{-4} kg CO_2 eq.	1	Open database
CH_4	1 10^{-4} kg CO_2 eq.	1	
Other emissions	0 kg CO_2 eq.	1	
Total direct emissions	4,62 kg CO_2 eq. / part	2,5	

Table 2: Example input/output calculation of CO_2-equivalent direct emissions for a gear wheel heat treating process.

Following the example of a gear wheel for an industrial crane gearbox, upon the calculation of indicators values for all processes defined in the process model in the first method phase, results must be resumed as illustrated in table 3:

	Energy demand		Energy cost		CO_2 emissions	
Process (level 2)	Value (kWh use energy / part)	Data quality coefficient	Value (€/ part)	Data quality coefficient	Value (kg CO_2 equivalent / part)	Data quality coefficient
Steel production	5,49	1,43	0,57	2	0,36	1,27
Soft machining	1,72	2	0,24	2	0,05	1
Heat-treating	41,23	3	2,26	3	4,62	2,5
Hard machining	2,55	2	0,36	2	0,08	1
TOTAL	50,99	2,11	3,43	2,25	5,11	1,44

Table 3: Results of the inventory and energy demand assessment of a gear wheel manufacturing process.

4.4 Phase 3: Results analysis and definition of improvement measures

This phase has two main goals: Finding critical points and defining measures to improve the analyzed process. Different measures can be defined at different process levels (cf. Figure 1). The method proposes to search critical points and define measures not only in the manufacturing process but also in other domains:

Measures in manufacturing-related processes

Measures can be determinate for the processes defined in phase 1 (goal and system definition). This can concern direct technical changes to equipment and manufacturing organizational changes such as new logistics solutions, alternative processes, etc.

Measures at the product development stage

Decisions taken during the product development process, especially in the early stages, have a strong influence on the environmental performance of manufacturing processes [13]. The results of the inventory and energy demand assessment can assist product designers with changing product features to improve future manufacturing.

Company-organizational measures

In some cases, it is necessary to implement measures on the organizational level such as changes to the company's environmental-/ energy-management system. These measures can concern different organizational levels e.g. from changing corporate policies to staff trainings in Production Planning and Product Development.

Measures in other areas

This domain concerns measures in areas not previously defined. This applies, for instance, to factors that affect internal manufacturing process and apply outside the company.

Since measures strongly depend on specific company characteristics, the MEDA method only includes a list of possible measures for the most common issues.

5 VALIDATION OF THE CONCEPT – CASE STUDY OF A GEARWHEEL MANUFACTURING PROCESS

In this chapter, the concept has been tested exemplarily in a manufacturing company in Germany on the basis of the **internal** manufacturing process of a gear wheel for an industrial crane gearbox. As shown in Figure 1 (cf. chapter 4), the main manufacturing sub-processes for this product include: raw material production, soft machining, heat treating and hard machining. The results have been used by the production planning department of the company to define a first set of measures.

Pursuant to the MEDA method, the following indicators have been calculated: energy demand (based on energy consumption data), energy costs and CO_2-equivalent emissions (cf. 4.3). In addition to this, quality coefficients have been determined for each data set. Tables 1, 2, and 3 summarize the analysis results (cf. chapter 4). The method stage 'results analysis and definition of improvement measures' is briefly summarized in the following.

The energy demand analysis illustrates that two processes are of utmost importance: the production of steel and heat treatment. Hence, these processes have the biggest potential for possible optimization measures. The results of the mechanical processes show that, due to the short cycle times for the exemplary product, energy use is low. For other products, the energy use may instead be higher.

Energy costs show a similar picture. But here, except for heat treatment, the mechanical manufacturing process offers vast potentials for optimization as well.

The result of the CO_2 emissions shows that there is also an immense potential for optimization, which, in turn, demonstrates that the industry has to continue to work in this area to reduce emissions.

The comparison of the single quality coefficients clearly indicates the potential to optimize data quality. An example is the data measured during the mechanical processes, which is inconsistent. Moreover, the data from online data sources confirms that there is a necessity to optimize these sources.

Table 3 shows the critical processes, most importantly the production of raw material and heat treatment. Optimizations are, however, also possible with the other analyzed manufacturing sub-processes.

There are different possibilities to implement alternatives to the current process. An example is the use of water/water cooling. This leads to lower useable energy use and lower energy cost per part. The comparison of these results yet shows that there are only marginal differences between the two. The main source for the high energy demand is the use of gas due to the use of outdated furnaces. The company therefore decided to carry out a calculation of profitability on the basis of the analysis presented in this case study.

This case study has shown that the MEDA method has successfully met the requirements listed in chapter 3. One of the weak points is the acquisition of data with sufficient quality.

6 CONCLUSIONS AND OUTLOOK

The case study has shown that the MEDA method is suitable for the tested use scenario. Results show that with the support of the MEDA method, companies are capable of identifying and quantifying the most critical stages of their internal manufacturing processes. This information can be an important first reference for defining appropriate measures in future production planning and product development.

Future work will comprise the testing of the method within a larger, more complex manufacturing process, in order to verify that the method can be applied in different kinds of manufacturing processes (mass production, batch production etc.). A requirement which has not been tested in the case study is the feedback of the results into product development, which remains an aspect for future work. Moreover, the method for the evaluation of data quality will be improved. Another aspect that has only been considered marginally is the consideration of laws, standards, and labels. Future extension of the method will include a solution for compliance checking against regulatory constraints.

Considering the specific needs of the company where the concept has been validated, a first rudimentary prototype of an IT tool has been developed to improve the application of the MEDA method. In order to facilitate companies consider energy efficiency, an enhanced IT tool must be developed. A particular goal of this tool is to enable the consideration of consequences of manufacturing processes as early as possible in the product development phase. That way, the integration of production planning and product development processes will increase.

7 ACKNOWLEDGMENTS

We express our sincere thanks to the Graduate School of Energy-Efficient Production and Logistics (Ruhr-Universität Bochum and TU Dortmund) for their support.

8 REFERENCES

[1] Abramovici, M., Quezada A., Schindler T., 2012, IT support for eco design - state of the art and research requirements, Proceedings of the GCSM Istanbul 2012, 488-493.

[2] Abramovici, M., Quezada A., Schindler T., 2013, Industry Requirements for an Assistant System Supporting Energy-Efficient Product Development in the Automotive Supply Industry, Proceedings of the 23rd CIRP Design Conference Bochum 2013, 989–997.

[3] Wagner, H.-J., 2011, Energieaufwendungen, Ökobilanzierung und Umwelt. Lecture notes chair Energy Systems and Energy Economics (LEE), Ruhr-Universität Bochum, Germany.

[4] Töpfer, A., 1996, Prozesskettenanalyse und –optimierung: State of the Art – Ansatzpunkte und Anforderungen, Geschäftsprozesse analysiert und optimiert, Luchterhand Verlag, Neuwied, Berlin, Germany

[5] VDI, 2012, VDI 4600 Cumulative Energy Demand Terms, definitions, methods of calculation, Beuth Verlag GmbH, Berlin, Germany

[6] DIN, 2011, DIN EN ISO 50001:2011 Energy management systems - requirements with guidance for use, Beuth Verlag GmbH, Berlin, Germany

[7] Schieferdecker, B., 2006, Energiemanagement-Tools-Anwendung im Industrieunternehmen, Springer Verlag, Berlin, Germany

[8] Erlach K., 2009: Energiewertstrom - der Weg zur energieeffizienten Fabrik, Fraunhofer Verlag, Stuttgart, Germany

[9] Krcmar, H., Dold, G., Fischer, H., Strobel, M., Seifert, E., 2000, Informationssysteme für das Umweltmanagement. Das Referenzmodell Eco-Integral, Oldenbourg Wissenschaftsverlag, Germany.

[10] Rünger, G., Götze, U., Putz, M., 2010, IT Systems Integration for the Development of Energy-Efficient Products, 677-698, Chemnitz, Germany

[11] Norris, G. A., 2001, Integrating Life Cycle Cost Analysis and LCA, The international Journal of Life Cycle Assessment, Jg. 6, H. 2, 118-120

[12] DIN, 2012, ISO/DIS 14067.2:2012 Greenhouse gases – Carbon footprint of products, Beuth Verlag GmbH, Berlin, Germany.

[13] Abele, E., Anderl, R., Birkhofer, H., Rüttinger, B, 2008, EcoDesign - Von der Theorie in die Praxis, Springer, Heidelberg, Germany.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

19.4 Monitoring production systems for energy-aware planning and design of process chains

M. Swat [1], T. Stock [2], D. Bähre [1], G. Seliger [2]
[1] Institute of Production Engineering, Saarland University, Saarbrücken, Germany
[2] Department for Machine Tools and Factory Management, Technische Universität Berlin, Germany

Abstract
Various energy-relevant data can be acquired from monitoring equipment and processes in production systems. Systematic analysis of these data is the basis for predicting the energy consumption of the production system and its energy-consuming elements. In order to continuously reduce the energy consumption in manufacturing, a new approach for the acquisition, aggregation and evaluation of these energy-relevant data throughout the production systems lifecycle is needed. This paper describes how energy-relevant data can be used for both the energy-efficient production planning and control and the energy-aware planning and design of the production system. Therefore, the comparability of equipment and processes in the data acquisition phase and the planning phase will be considered.
Keywords:
Energy consumption, predictive planning, methodology

1 INTRODUCTION

Climate change and other environmental consequences of human energy consumption are likely to be one of the most important challenges and threats to the global economic security in the next decades [1]. Therefore, several countries pursue a transition towards a sustainable energy provision and use. This comprises means such as renewable energy, energy efficiency and energy conversation. Industry is one of the keystones to realize this endeavor. Hence, the challenges for manufacturing companies are to increase energy efficiency and make energy consumption and the related energy costs a manageable resource in the future. Thereby, one focus is on electric energy which is widely used due to its flexibility and wide range of application [2]. In 2010, the industrial sector accounted for about 41 % of the electrical energy consumption worldwide [3].

In order to gain transparency, companies start to implement energy monitoring systems in their production systems. Therefore, more and more real-time measurement systems are used for monitoring the energy consumption on machine level. These energy consumption data can be the starting point for the energy-aware planning and design of the production system. During the actual use phase, the energy consumption data can be applied for the energy-aware control of the production system. Additional potential for long-term reduction of energy consumption promises the usage of the same pool of data for the design of the production system during the planning phase [4]. The objective of this paper is to show how the energy monitoring data can be used throughout the production systems lifecycle.

2 ENERGY-AWARE PLANNING AND DESIGN

2.1 Planning process and planning object

In production systems, energy, material and information are combined to realize the transformation of raw materials into desired end products [5]. Regarding electricity monitoring, the levels of application can be divided into the factory level, the department level and the unit process level according to [2]. This paper refers to the electricity monitoring on the level of unit processes that combine to process chains. Process chains describe the technical and organizational way how the transformation is achieved. In this sense they are the nucleus of a production system and build the starting point for the planning activities in the development of production systems for the series production. The planning can be separated into the activities that occur once in advance to the realization of the process chain and the recurring planning after the realization. All planning activities that occur once in advance to the realization are attributed to the technical production planning (TPP) [6]. In contrast, the production planning and control (PPC) is concerned with adjusting output and logistic performance with market demand by allocating customer orders and company resources over time [7].

The TPP comprises the selection of technologies and their combination to process chains, the selection of manufacturing equipment and the definition of process parameters [8]. There is a wide range of research activities to consider energy consumption aspects in these early steps of TPP. For example, the energy and resource efficiency has been compared for alternative process chains [9-10]. Another research field is the determination of energy-related lifecycle costs of machine tools in order to consider these as one criterion during the procurement [11]. The impact of alternative process parameters on the energy consumption has been investigated in [12] based on a discrete-event simulation. However, all approaches are challenged by the effort for the investigation and prediction of the energy consumption. A comprehensive approach for the use of energy monitoring data can help to overcome this obstacle.

Energy-aware PPC is basically addressed by two different approaches in current research. The first approach is simulation-orientated by using material-flow-simulation for the development and validation of various production strategies considering the energy consumption of the manufacturing equipment. The second approach is based on methods of

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

operational research. The methods in general set up multi-objective optimization problems. The objective function of these problems usually contains productivity as well as energy targets. Energy-aware simulation models of a production system in current research are set up on the basis of Energy Blocks [13] or integrated process modules with measured energy profiles [14] and consider the energy consumption of peripheral systems [15]. The objective functions of energy-aware multi-objective optimization are addressing the total energy consumption of a production system [16], the peak load [17] and electric power costs respectively the time-of-use electricity prices [18].

2.2 Methods to obtain energy planning data

The energy-related planning activities in TPP and PPC are based on the availability of power consumption and time parameters that allow the calculation of the energy consumption. There are three general methods for determining the energy consumption data of manufacturing equipment in process chains: *Experimental measurements* are discontinuous and one-time measurements. Such measurements are performed in laboratory or in production environments in order to gain insight into the energy consumption of unit processes or to determine the efficiency of manufacturing equipment [19]. In contrast, the *monitoring* of process chains is characterized by the continuous measurement and evaluation of the energy consumption. Thus, the energy monitoring is capable of creating energy awareness and foster energy efficiency by including the monitoring feedback in the manufacturing management system [20]. The frequency of the measurements for monitoring depends on the specific purpose. The *simulation* of the energy consumption with simulation models allows for determining the energy consumption without performing power measurements, once the models are available [12]. However, for building the simulation models, experimental measuring or monitoring is necessary. The more accurate the simulation model is intended to be, the more effort must be put into the previous measuring and modeling. Following, an approach for the energy-aware PPC and TPP based on the energy monitoring in process chains is presented.

3 APPROACH FOR ENERGY-AWARE PLANNING

3.1 Monitoring strategy

The definition of a monitoring strategy is the initial point for the energy-aware planning and design of process chains based on the energy monitoring of manufacturing equipment. Applying the defined monitoring strategy ensures consistency and transparency for the implementation of energy monitoring systems. The monitoring strategy depicted in Figure 1 comprises a strategy for measuring and evaluation of the energy consumption data.

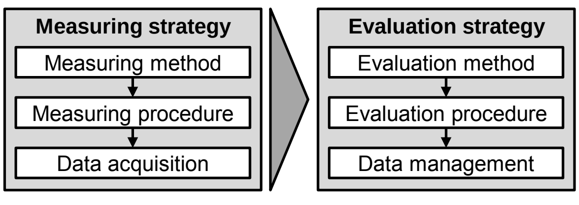


Figure 1: Monitoring strategy, following [19].

First, the *measuring method* is defined. This includes the definition of the traced quantity with the according unit, the definition of the applied measuring devices and the temporal output resolution. Measuring devices need to be selected according to the measuring task considering the cost, communication interfaces and the temporal output resolution. A temporal output resolution of 1 sample per second is sufficient in terms of accuracy of the measurement and the manageability of the data stream in further processing for low and highly dynamic manufacturing processes [2]. In the next step, the *measuring procedure* specifies what, where and when is to be measured. The system boundary ("what") of the measuring procedure is set to single unit processes that combine to process chains. The energy consumption of a unit process is composed of the energy consumed by the manufacturing equipment, e.g. lathe or milling machine, and the energy consumed by peripheral systems such as lubricant and compressed air supply. However, in a first step the energy consumption of peripheral systems is not considered. The main connection of the manufacturing equipment is defined as the measurement point ("where"). Hence, the equipment is characterized by its operational state and its state-related power demand. The measurement routine ("when") includes the length of measurements and the number of repeated measurements. In case of continuous measurements the routine is fully determined by the measurement output resolution of 1 sample per second. Finally, the *data acquisition* specifies the data capturing. This includes the definition of interfaces and mechanisms for the data communication [21]. For the subsequent evaluation of the measured data it is especially important to assign additional information such as a timestamp, the operational state, the equipment number, the product manufactured during the measurement and the set of applied process parameters.

The evaluation strategy provides instructions how the captured data are to be processed and made available for analysis and further application. The *evaluation method* describes how and which parameters are to be built and how they are derived from the captured data. Therefore, basic methods of descriptive statistics such as mean value, standard deviation and frequency distribution are applied [22]. Figure 2 displays a power consumption profile of the manufacturing equipment for a honing process.

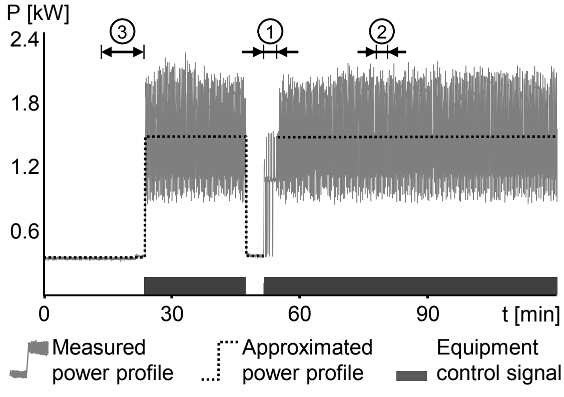


Figure 2: Evaluation of a captured consumption profile.

The chart shows the cutout of two hours from series production. A control signal of the equipment was tracked to document the operational state. The signal is activated with every start of a machining cycle and makes it possible to distinguish the operational state when the equipment is processing from the state when the equipment is waiting for parts. The chart shows two characteristic operational states in terms of the consumed power. In the state *process* the manufacturing equipment carries out the actual machining cycles. The state *idle* defines that the equipment is ready for operation. No machining is carried out, hence no control signal is tracked. A third operational state where the equipment is switched off does not appear in the shown profile.

Section 1 in the profile shows a power consumption different from the operation even though a machine signal was tracked. This presents an operational state that is caused by unpredictable manual interference. From time to time, those states can be observed. However, the occurrence is negligible for this investigation. Thus, the power consumption profile and the related power consumption can be approximated by averaged power consumption parameters and the frequency of occurrence of the operational states. An overview of the power consumption and time parameters is given in Table 1.

Table 1: Overview of power and time parameters.

Operational state	Power consumption parameter [kW]	Frequency of occurrence [%]
Off	P_{off}	$f_{off\,Ø}$
Idle	$P_{idle\,Ø}$	$f_{idle\,Ø}$
Processing	$P_{process\,Ø}$	$f_{process\,Ø}$

In the next step, the *evaluation procedure* determines how the parameters can be computed from the captured power consumption profiles. In Figure 2 it can be seen that the mean power consumption varies from cycle to cycle in the processing state. This is due to some random variations within the manufacturing equipment. Therefore, the average power consumption for the state *process* ($P_{process}$) is calculated for each cycle. When $P_{process}$ is averaged for the measured number of cycles, the desired power consumption parameter $P_{process\,Ø}$ can be derived. This was done for 10 cycles indicated by section 2 in Figure 2. Deviations in the power consumption during processing may also occur due to the wear of tools and components of the equipment. Provided systematically planned tool replacement and maintenance of the equipment, the parameter $P_{process\,Ø}$ is a reliable average power consumption value for manufacturing equipment. The associated standard deviation (SD) indicates the variability of the parameter. For the state *idle* there is no temporal reference given, that could be used for calculating the power consumption parameter $P_{idle\,Ø}$. Therefore, a reference interval of 60 s is chosen. Section 3 in Figure 2 indicates a segment of 10 such intervals, i.e. 10 minutes, in the power consumption profile. The calculation procedure for section 2 and 3 is exemplarily shown in Table 2. Obviously, the value for the third power consumption parameter P_{off}, when the equipment is switched off, is zero.

In the same way, the frequency parameters for the operational states can be calculated. In contrast to the power consumption, the frequency is not given in the absolute unit, i.e. hours, but it is expressed in percent from the total time period under consideration. Based on the weekly frequency of occurrence, a yearly average frequency of occurrence and a standard deviation can be calculated.

Table 2: Computation of power consumption parameters.

No. of interval	P_{idle} per interval [kW]	No. of cycle	$P_{process}$ per cycle [kW]
1	0.35	1	1.51
2	0.35	2	1.50
3	0.35	3	1.56
4	0.35	4	1.57
5	0.35	5	1.56
6	0.35	6	1.53
7	0.34	7	1.51
8	0.35	8	1.54
9	0.37	9	1.56
10	0.37	10	1.57
$P_{idle\,Ø}$	**0.35**	**$P_{process\,Ø}$**	**1.54**
SD	**0.01**	**SD**	**0.02**

It has to be mentioned that in comparison to the power consumption parameters these time parameters are highly influenced by the organizational conditions, i.e. the demand for the produced parts. However, the averaged parameters give a realistic picture of the past and they are therefore a good basis for future planning activities. Finally, the *data management* completes the monitoring strategy.

3.2 Data management

A key aspect for the efficient use of the data in the energy-aware PPC and TPP is a comprehensive concept for the management of the monitored data. There are three main determining factors that influence the energy consumption parameters: the manufacturing equipment, the machining task and the set of process parameters. The manufacturing equipment can be structured into classes according to the machine type, i.e. milling machines or honing machines. A further classification based on the power class, the type of construction and the model is advisable [13]. The manufacturing task comprises all operations that are carried out by the manufacturing equipment during one cycle. As differing machining tasks will affect the energy consumption parameters, a classification of the machining tasks is necessary according to the operations that are performed. The third determining factor is the set of process parameters that is applied, e.g. the number of revolutions, feed rate and depth of cut for a turning process. Looking at the influence of the three determining factors on the energy consumption parameters it is clear that the power consumption in the idle state ($P_{idle\,Ø}$) solely depends on the type of manufacturing equipment. In contrast, the power consumption for the processing state ($P_{process\,Ø}$) can significantly vary for a specified type of manufacturing equipment depending on the machining task and the set of process parameters. In order to provide sufficiently accurate planning data for different planning cases, a new data set is created for every distinct combination of these determining factors. The number of data sets will be reasonable in the particular case of a company and its particular product portfolio. The concept for the data management is illustrated in Figure 3 as a so-called EnergyCube. In the EnergyCube, each small cube can be thought of as a set of energy planning data including the power consumption parameters and the frequency of occurrence of the operational states. Note that the concept of the EnergyCube is independent from the method applied for the representation of the power consumption profile, i.e. the number and kind of operational states or the representation with another concept, e.g., the Energy Block concept [13].

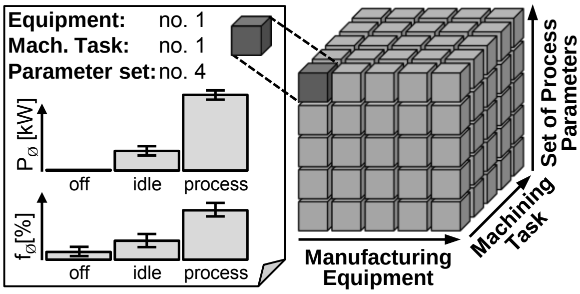


Figure 3: Concept for data management with the EnergyCube.

By means of the EnergyCube concept the monitored energy consumption data can be provided as planning data for the energy-aware PPC and TPP. While both planning tasks have different requirements, they can use the same data base. In case of a planning request for the energy-aware PPC, the planner selects the required information according to the manufacturing equipment, the machining task and the set of process parameters specified in the planning request. The planning request in the TPP is less detailed as the manufacturing equipment, the machining task and the set of process parameters may not have been fully defined. The more detailed the planning requests become, the more accurate the data sets can be selected. In the course of TPP also new technologies that have not yet been operated in the company may be considered for future process chains. In this case, lifecycle inventory data bases or the cooperation with the equipment manufacturer can be a practicable way to estimate and include the energy consumption of the planned process in the further planning. Figure 4 summarizes the approach for the data management.

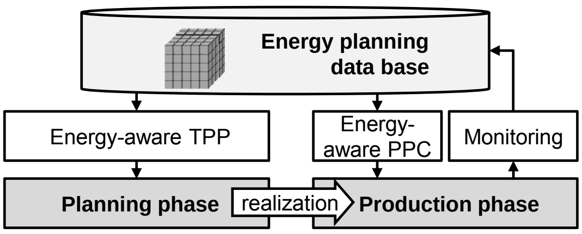


Figure 4: Management of monitoring data.

3.3 Energy-aware PPC

Within the scope of energy-aware PPC energy-based objectives are considered along with conventional productivity objectives such as short throughput time of a product, high utilization of manufacturing equipment and meeting target dates of customer orders. For instance, low energy consumption of manufacturing equipment, avoiding power peak loads within a production system and low energy costs of production based on volatile energy prices are taken into account. The first task for realizing energy-aware PPC is to combine each costumer's order as represented by a certain job with energy consumption. Each job is thereby characterized by a certain lot size and a specific process sequence for relevant manufacturing equipment. The sequence results from the equipment bill of material for the product. The deduction of the energy consumption from the process sequence of a job is shown in Figure 5. On each machine a job passes one determined machining task with predefined process parameters. The energy consumption for this machining task depending on process parameters and manufacturing equipment is represented by individual cubes within the EnergyCube. The average power consumption for the processing state $P_{process\,Ø}$ is revealed thereof. In addition, the average power consumption for the idle state $P_{idle\,Ø}$ of a machine is part of the parameter set.

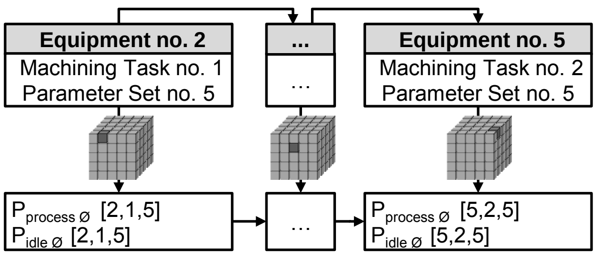


Figure 5: Example of a process sequence for equipment of a scheduling job with related machining tasks and parameters.

The second task for realizing energy-aware PPC is to set up the energy-based scheduling problem on the basis of $P_{process\,Ø}$ and $P_{idle\,Ø}$ of each machine. Figure 6 shows a scheduling chart for machine allocation taking the power consumption into account. Hereby, each order is dispatched to a machine according to its specific process sequence. In order to realize an energy-aware machine allocation, the following energy-based objectives and constraints for a multi-objective scheduling problem can be set up: (1) minimize the total idle time of the production system, (2) shut down machines at the right time, (3) minimize the total energy costs considering time-dependent energy prices, (4) avoid power peak loads and (5) meet the agreements of the energy contract by e.g. avoiding an overrun of a limit for the peak load.

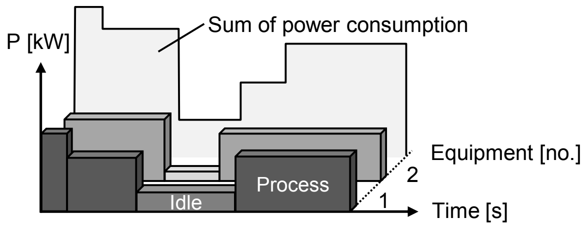


Figure 6: Machine allocations of scheduling jobs with related power consumption.

3.4 Energy-aware TPP

The planning objectives of the energy-aware TPP are the Technology Planning as well as the Configuration Planning for the design of a new process chain for the manufacture of one or different product(s), as presented in Figure 7. Thereby, the Technology Planning includes the energy-aware selection of manufacturing task, manufacturing equipment and process parameters for each production task needed to manufacture the product. The Configuration Planning contains the allocation of manufacturing equipment and machining tasks.

Additionally, it also implies the determination of the process sequence of the manufacturing equipment. Both planning objectives must be considered holistically and have to be matched with one another in order to realize the best possible level of target achievement.

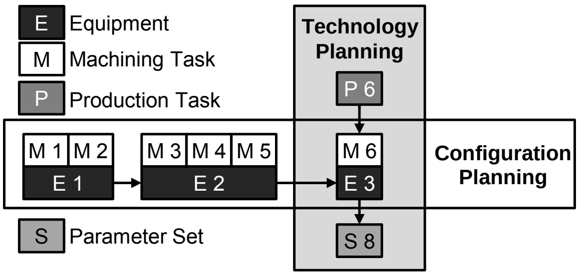


Figure 7: Planning levels for a holistic TPP.

The sequences of the Technology Planning steps are described in the following. The *Selection of Manufacturing Process* is the first planning step. The appropriate manufacturing process is allocated to the specific production task. The sequence of production tasks is derived from the design of the product and represents the fixed order of tasks to process the manufacturing of the product. Thereby, a production task is defined as a task for manufacturing a geometrically determined attribute of the product [23] by the implementation of a specific main group of manufacturing processes according to DIN 8580 [24]. A production task could be for instance: create a hole with the diameter 30 mm by using cutting. Now within the first planning step this productions task is allocated to a certain subgroup of manufacturing processes, e.g. drilling, countersinking, reaming. The second planning step is the *Determination of Machining Task*. The machining task is hereby the technology-based equivalent of the production task for one specific sub group of manufacturing processes, e.g. drilling a hole with the diameter 30 mm. Since this sub group is in addition represented by a specific EnergyCube, the appropriate machining task is determined within this EnergyCube. The fixed sequence of machining tasks for processing the manufacturing of the product is specified after this planning step has been executed for every production task. The third and fourth planning step *Selection of manufacturing equipment* and *Selection of Parameter set* must be matched with the Configuration Planning. For the defined machining task alternative suitable and available machines are selected. For each machine the parameter set is then chosen from the EnergyCube. Herewith two cases have to be considered. The first case occurs when a parameter set already exists within the EnergyCube which completely provides the machining boundary conditions for the considered machining task in dependency of the manufacturing equipment and the product. In this case, the defined parameter set and machining task determine the power consumption $P_{process\,Ø}$, $P_{idle\,Ø}$ and the time parameter $f_{process\,Ø}$, $f_{idle\,Ø}$ for the specific machine by the related cube. The second case describes the situation where no suitable parameter set can be ascertained for the planning task within the EnergyCube. In this situation, power consumption and time parameters have to be approximated from existing parameter sets. Finally, the processing time ($t_{process}$) for each machining task depending on a specific machine and parameter set has to be approximated. This processing time is then used together with the related power consumption and time parameters in order to calculate the energy consumption of a machining task:

$$E_{machinig\ task} = P_{process\,\emptyset} \cdot t_{process} + \\ +P_{idle\,\emptyset} \cdot \left(t_{process} \cdot \frac{f_{idle} + f_{process}}{f_{process}} - t_{process} \right) \quad (1)$$

The selection of alternative machines for every machining task with the dedicated energy consumption can then be used as input for the Configuration Planning. Within this scope, each machining task is finally allocated to one certain machine. Simultaneously, the process sequence of machines is set. These actions are carried out considering the abovementioned fixed sequence of machining tasks. In order to conduct the Configuration Planning, the following productivity and energy-based objectives can be considered in order to set up a multi-objective scheduling problem: (1) minimize the quantity of manufacturing equipment, (2) minimize the throughput time of the product, (3) minimize the total power consumption of the process chain. Furthermore the following productivity constrains have to be taken into account: (1) allocate all machining tasks and (2) meet the correct sequence of machining tasks.

4 INDUSTRY CASE

The industry case is derived from an ongoing research project with a manufacturing company in Europe. The company manufactures various components for the automotive industry in series production, e.g., crankshafts. The reduction of high energy consumption and energy-related costs was identified to be one measure to sustainably improve the company's economic and ecologic performance. In order to realize this goal, the company implemented a real-time measuring system for the energy consumption.

The measurements are executed on every machine of a process chain for the manufacture of the crankshafts. The monitoring infrastructure includes metering devices for the power measurement, a programmable logic controller (PLC) and an industrial PC connected to a server for analyzing the data stream. This real-time data stream of the power consumption for each machine is aggregated according to the presented monitoring strategy. In order to distinguish the operational states, the measured power data were matched with the data from a Supervisory Control and Data Acquisition system (SCADA). This matching of data is still a critical process because the data of the SCADA system are not necessarily consistent with the power consumption data. The application of the implemented monitoring system allows for deriving the EnergyCubes for the investigated process chain for crankshafts. These data are now available for the energy-aware PPC and can also be used for the TPP of a process chain for a new variant of crankshafts. Potential for the presented approach can be identified for the energy-aware TPP where the energy consumption can be included as one criterion for the design of manufacturing process chains, i.e., the selection of processes and manufacturing equipment.

5 SUMMARY

In this paper, energy monitoring in production systems was proposed as a starting point for the energy-aware planning and design of manufacturing process chains. In order to achieve this aim, a comprehensive approach was worked. The following results can be gained from this paper:

- A monitoring strategy for consistent and transparent implementation.
- Parameters for power and time consumption of manufacturing equipment using basic statistic methods.
- The framework of EnergyCubes for the management of the energy data sets.
- A procedure for a simultaneous energy-aware technology and configuration planning of process chains on the basis of EnergyCubes.
- A procedure for connecting EnergyCubes to scheduling jobs for subsequent energy-aware optimization of machine allocation

Finally, an industry case illustrated the chances and challenges of the presented approach. Future work will focus on a detailed description of the planning procedures for technical production planning (TPP) and production planning and control (PPC).

6 ACKNOWLEDGMENTS

This research was supported by the project *enPROchain* funded by the program “Zentrales Innovationsprogramm Mittelstand (ZIM)“ of the German Ministry of Economics (BMWi), by the *KAP* research project funded by the “Seventh Framework Programme” of the European Commission and supported by the Kadia Produktion GmbH + Co.

7 REFERENCES

[1] Editorial, 2012, Past and prospective energy transitions: Insights from history, Energy Policy, 50, 1-7.

[2] Kara, S., Bogdanski, G., Li, W., 2011, Electricity Metering and Monitoring in Manufacturing Systems, 18th CIRP International Conference on Life Cycle Engineering, 1-10.

[3] International Energy Agency, 2012, Key World Energy STATISTICS, http://www.iea.org/publications/free publications/publication/kwes.pdf, retrieved 15.04.2013.

[4] Müller, E., Engelmann, J., Strauch, J., 2008, Energieeffizienz als Zielgröße in der Fabrikplanung, wt Werkstattstechnik online, 98, 7/8.

[5] Spur, G., 2008, Produktion, Hütte - Das Ingenieurwesen, Springer.

[6] Zenner, C., 2006, Durchgängiges Variantenmanagement in der Technischen Produktionsplanung, PhD Thesis.

[7] Wiendahl, H.-P., ElMaraghy, H.A., Nyhuis, P., Zäh, M.F., Wiendahl, H.-H., Duffie, N., Brieke, M., 2007, Changeable Manufacturing - Classification, Design and Operation, Annals of the CIRP - Manufacturing Technology, 56/2, 783-809.

[8] Klocke, F., Fallböhmer, M., Kopner, A., Trommer, G., 2000, Methods and tools supporting modular process design, Robotics and Computer Integrated Manufacturing, 16, 411-423.

[9] Reinhart, G., Reinhardt, S., Föckerer, T., Zäh, F., 2011, Comparison of the Ressource Efficiency of Alternative Process Chains for Surface Hardening, 19th CIRP International Conference on Life Cycle Engineering, 311-316.

[10] Swat, M., Brünnet, H., Bähre, D., 2013, Selecting manufacturing process chains in the early state of the product engineering process with focus on energy consumption, Technology and Manufacturing Process Selection: the Product Life Cycle Perspective, Springer. Accepted for publication.

[11] Kuhrke, B., 2011, Methode zur Energie- und Medienbedarfsbewertung spanender Werkzeugmaschinen, PhD Thesis.

[12] Larek, R., Brinksmeier, E., Meyer, D., Pawletta, T., Hagendorf, O., 2011, A discrete-event simulation approach to predict power consumption in machining processes, Prod. Eng. Res. Devel., 5, 575-579.

[13] Weinert, N., 2010, Vorgehensweise für Planung und Betrieb energieeffizienter Produktionssysteme, PhD Thesis.

[14] Thiede, S., 2012, Energy efficiency in manufacturing systems, Springer.

[15] Haag, H., Siegert, J., Bauernhansl, T., Westkämper, E., 2012, An Approach for the Planning and Optimization of Energy Consumption in Factories Considering the Peripheral Systems, Leveraging Technology for a Sustainable World, Springer, 335-339.

[16] Mouzon, G., 2008, Operational Methods and Models for Minimization of Energy Consumption in Manufacturing Environment, PhD Thesis.

[17] Fanga, K., Uhana, N., Zhaob, F., Sutherland, J.W., 2011, A new approach to scheduling in manufacturing for power consumption and carbon footprint reduction, Journal of Manufacturing Systems, 30, 234-240.

[18] Luo, H., Du, B., Huang, G.Q., Chen, H., Li, X., 2013, Hybrid Flow Shop Scheduling Considering Machine Electricity Consumption Cost, International Journal of Production Economics, Elsevier, Accepted for publication.

[19] Zein, A., 2012, Transition Towards Energy Efficient Machine Tools, PhD Thesis, Springer.

[20] Bogdanski, G., Spiering, T., Li, W., Herrmann, C., Kara, S., 2012, Energy Monitoring in Manufacturing Companies – Generating Energy Awareness through Feedback, 19th CIRP International Conference on Life Cycle Engineering, 539-544.[21] Eberspächer, P., Haag, H., Rahäuser, R., Schlechtendahl, J., Verl, A., Bauernhansl, T., Westkämper, E., 2012, Automated Provision and Exchange of Energy Information throughout the Production Process, 19th CIRP International Conference on Life Cycle Engineering, 381-386.

[22] Ross, S., 2009, Introduction to probability and statistics for engineers and scientists, Elsevier.

[23] Tönshoff, H.K., Denkena, B., 2012, Übersicht über die Fertigungsverfahren, Dubbel - Taschenbuch für den Maschinenbau, Springer, S1-S3.

[24] DIN 8580, 2003, Manufacturing processes – Terms and definitions, Beuth.

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

19.5 A theoretical energy consumption prediction model for prismatic parts using STEP AP224 features

R. Sercan Altıntaş [1], M. Ural Uluer [2], H. Özgür Ünver [1], S. Engin Kılıç [2]
[1] Department of Mechanical Engineering, TOBB University of Economics and Technology, Turkey
[2] Department of Mechanical Engineering, Middle East Technical University, Turkey

Abstract

The rate of global warming increases sharply, thus energy and resource efficiency in manufacturing gain vital importance. In order to increase energy and resource efficiency, first consumed energy amount must be quantified accurately for each manufacturing process. Furthermore, CO_2 is one of the top green house gases that contributes to global warming and its emission can be derived from the quantified energy consumption data. In this study, a prediction model for determining theoretical energy consumption during the manufacturing processes of prismatic parts is presented. The prediction model relies on the STEP Application Protocol 224 features for volumetric information and material properties of prismatic parts.

Keywords:

Process Energy Prediction; Energy Efficient Manufacturing; Carbon Footprint

1 INTRODUCTION

The rise of human population and industrialization have pioneered the rise of energy consumption so that the world's energy demand is expected to be 47% higher in 2035 than current levels [1]. With increasing demand of energy, the concern about energy availability and its environmental impacts are growing. Despite expected increase in the use of renewable sources for electricity generation, most of our electricity is likely to be generated from carbon based energy sources such as coal, natural gas and petroleum over the next years [1]. The U.S., one of the leading countries in energy consumption, gathers 83% of energy from carbon emitted sources and this ratio is expected to be 78% in 2035. Figure 1 illustrates U.S.'s primary energy sources in energy production [2]. Carbon based energy sources accounts more than half of the world's greenhouse gas emissions [3].

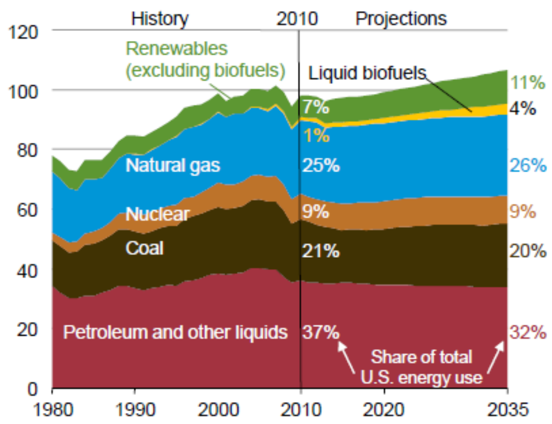


Figure 1: Primary energy sources in the U.S. [2].

In U.S., the most energy consumed end-use sector is industrial sector with 31% of total consumption [4]. Figure 2 depicts the share of industrial sector among the other end use sectors. Moreover, industrial energy consumption is expected to show the second largest increase in total primary energy use by the end of 2035 [4]. Manufacturing activities are also held on 19% of the world's greenhouse gas emissions [5].

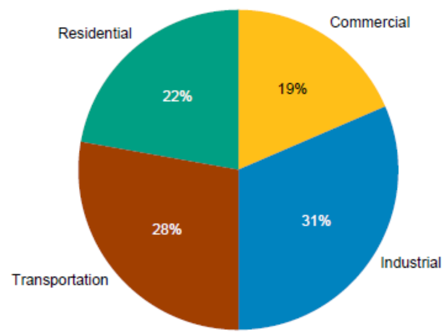


Figure 2: End use sector shares of total energy consumption in U.S. [4].

With the expectation of rise in industrial energy consumption and electiricity costs, energy efficiency gains vital importance. Most of the G-20 countries attempt to build energy efficiency policies such as energy certification schemes, regulatory building codes, tax reductions etc. [6]. In order to use energy more efficiently and reduce carbon emissions, first the energy used for each manufacturing process should be monitored. Then reduction strategies can be developed and energy efficient work shops can be created.

Machining is one of the manufacturing operations that is widely used at industrial sector to produce finished goods. Machining is a material removal process which aims to generate the shape of the workpiece from raw material or to improve the surface quality of the previously formed workpiece by removing redundant material in the form of chips [7]. A machining operation can be a cutting process such as turning, milling, drilling etc. or an abrasive process

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

such as grinding, honing, lapping etc. [8]. Milling is one of the most versatile cutting processes, and it is inevitable for the manufacturing of prismatic parts.

In this study, a theoretical energy consumption prediction model for prismatic parts utilizing STEP AP224 features is proposed. Theoretical energy consumption calculation is based on the tool tip energy consumed to remove the predefined STEP AP224 features. The ultimate aim of this study is to develop a software that predicts theoretical energy consumption and calculates carbon emissions of each STEP feature which is designed and machined afterwards. This information can provide engineers the knowledge of the environmental impacts of the part at design stage. Software developing phase is still an ongoing process and a model for determining auxiliary energy consumption is planned as a future work.

2 FEATURE BASED DESIGN AND STEP

CAD Systems provide engineers a platform to design part models with geometrical and topological data. This low level representation of data is inadequate to denote the part model in downstream applications such as CAM and CNC activities. In order to represent the part model data with a high level of information feature modeling was introduced. Features provide not only geometrical and topological data but they also provide tolerances, material specification and surface finish data. The creation of features are separeted into two categories: Feature Based Design (FBD) and design with feature recognition. FBD is based on creating a part from predefined features stored in a feature library. On the other hand, in design with feature recognition, features are obtained by geometrical data created by CAD software [9,10].

FBD, which is planned to use in this study, keeps the dimension data as variables and defines the geometry of the features in order to instantiate the feature during modelling phase. FBD helps better understanding of the design intent and also makes explicit product data available in a neutral format which can be used directly with downstream applications.

2.1 Basics of STEP

To meet the natural requirements of feature technology, a few attempts were made by national organizations. IGES, VDFAS, SET data formats are among those attempts. They all represent the geometric aspect of the design well. However, they did not succeed in supplying high level of information between CAD and CAM systems. ISO 10303, formally known as STEP(Standard for the Exchange of the Product Model Data), is an international standard that aims to provide a natural mechanism capable of representing product model data throughout the life cycle of a product [11]. STEP, having a mechanism that is capable of describing a product independent from any other system, is a basis for implementing and sharing product databases and archiving [12,13].

STEP is organized as a series of parts, each published individually. These parts fall into one of the following series: application protocols (APs), description methods, integrated resources, application interpreted constructs, abstract test suites, implementation methods and conformance testing. STEP uses a formal specification language, EXPRESS, to define product data for both integrated resources and application protocols. The use of formal language enables accuracy and agreement of representation and aid development of implementations [11].

2.2 Feature Based Design with STEP AP 224

An application protocol (AP) includes the definitions of scope, context, and information requirements of an application. In this study, AP 224 (Mechanical Product Definition for Process Planning Using Machining Features) and its feature library are used. This application protocol specifies an application protocol for the representation of information needed to produce a mechanical part definition for process planning of a single piece or an assembly product for machining operations, and define the integrated resources necessary to meet these requirements [12]. A manufacturing feature defined as a shape that represents volumes to be removed by machining to obtain the final part geometry from the initial stock. Manufacturing features break down into three categories in STEP AP224: transition features, machining features and replicate features. Figure 3 illustrates the manufacturing features by their categories [9].

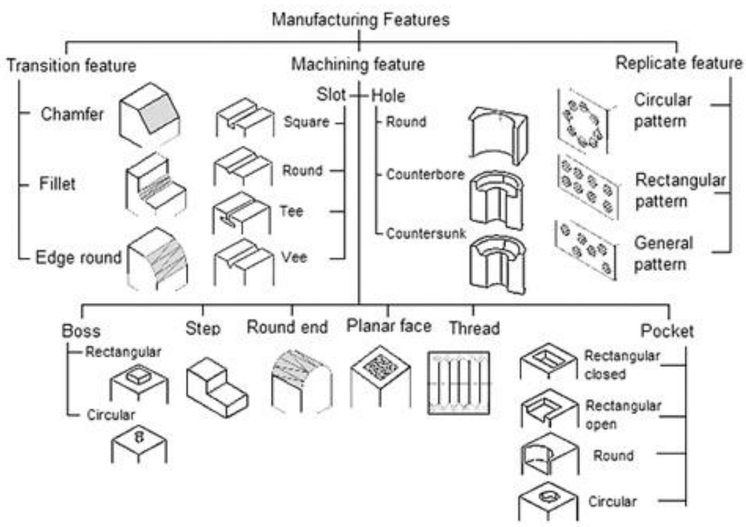


Figure 3: STEP AP 224 Manufacturing Features List [9].

Amaitik and Kılıç [9], represents STEP-FM (STEP-based Feature Modeller) in order to develop FBD system for designing prismatic parts using predefined STEP features. Modelling process in STEP FM starts with the selection of stock shape, then goes on with feature selection and feature parameters' definition. Feature parameters for hole features are listed in Table 1. The process continues with placement and orientation of the created feature. Feature modelling process ends with STEP data generation phase. Exported as STEP-XML data file format, the designed part can be used directly in donwstream applications since it contains high-level part data.

Table 1: Feature parameters of Hole feature.

HOLE	
Feature	**Parameters**
Round Hole	D, L, Bottom Condition
Tapered Round Hole	D, DF, L, Bottom Condition
Countersunk Hole	1st Hole, 2nd Hole
Counterbore Hole	1st Tapered Hole, 2nd Hole

3 THEORETICAL ENERGY ESTIMATION METHODOLOGY

Rahimifard et al. [14] divide energy consumption of manufacturing operations into two groups which are direct energy and indirect energy. Direct energy is defined as the energy of the required processes such as milling, turning, painting, etc. Indirect energy, on the other hand, is the consumed energy by the services to maintain required conditions for the work place such as lighting, heating, etc. Direct energy can be broken down into two sub-categories:

$$E_{direct} = \sum E_{process} + \sum E_{handling} \tag{1}$$

where $E_{process}$ is the energy consumed by manufacturing process and $E_{handling}$ is the energy consumed by the automated handling materials like robots and conveyors. Uluer et al. [10] defined the energy consumption while manufacturing a part by the following equation:

$$E_{part} = \sum E_{process} + \sum E_{handling} + \sum E_{indirect} \tag{2}$$

During a manufacturing process, like milling a manufacturing feature to a prismatic stock, there are two types of energy consumption [14].

$$E_{process} = E_{th} + E_{aux} \tag{3}$$

E_{th} is the theoretical energy which is required to carry out the actual metal removal processes. E_{aux} is the auxiliary energy which is consumed either by supplementary activities or by auxiliary equipments such as cooling pumps, tool changers, chip handling equipments. According to Dahmus and Gutowski [15] auxiliary energy consumption covers 30-50 % of the total energy consumption in automated milling machines. Auxiliary energy can be divided into two subgroups: constant auxiliary energy ($E_{aux\text{-}const}$) and variable auxiliary energy ($E_{aux\text{-}var}$) [10].

$$E_{aux} = E_{aux-const} + E_{aux-\mathrm{var}} \tag{4}$$

Constant auxiliary energy is the energy consumed by supplemental components or services, even when the machine is on standby mode. Operations such as lighting and components like embedded computer for the CNC machine tools are both examples for constant auxiliary energy. Variable auxiliary energy is time dependent and may change during machining operation. Energy consumption of servo motors, spindle motors and automatic tool changers are examples of variable auxiliary consumption. Li et al. [16] identified and classified auxiliary energy components:

$$E_{aux-const} = E_{computer} + E_{light} + E_{fan} + E_{misc} \tag{5}$$

$$E_{aux-\mathrm{var}} = E_{servo} + E_{spindle} + E_{ATC} + E_{cool} + E_{chiller} \tag{6}$$

3.1 Theoretical Energy Estimation Model

Theoretical energy consumption while milling a manufacturing feature can be determined by multiplying V_{rem} (mm^3), which is the removed material volume, with k_c (J/ mm^3), which is the specific cutting energy.

$$E_{th} = k_c \cdot V_{rem} \tag{7}$$

Since the milling operation is investigated in this study, the removed volume for each feature must be calculated autonomously. Also rough cutting volumes and finish cutting volumes for each feature must be calculated seperately. Specific cutting energy is defined as the energy required to remove a unit volume of material. For milling operations, k_c is calculated by the following equation [17]:

$$k_c = \frac{(1-0{,}01\cdot\gamma_0)\cdot k_{c^{1,1}}}{h_m^{m_c}} \tag{8}$$

where γ_0 (°) is the effective rake angle; $k_c^{1,1}$ (J/mm^3) is the specific cutting energy for 1 mm chip thickness and m_c is an exponent which varies with the material of the workpiece. h_m is the avarage chip thickness and calculated by the following equation [17]:

$$h_m = \frac{360\cdot f_z\cdot a_e}{\Pi\cdot D_c\cdot\omega_e}\cdot\sin\kappa \tag{9}$$

where f_z is the feed per tooth(mm/tooth), a_e (mm) is the width of cut, D_c (mm) is the cutter diameter, ω_e (°) is the engagement angle and is K the cutting edge angle.

3.2 Carbon Footprint Estimation Model

Jeswiet and Kara [18] have offered a model that calculates the carbon emissions of a manufacturing process directly from the consumed energy data. This method offers a Carbon Emission Signature (CES^{TM}) that has a unit of kg CO_2/GJ. CES^{TM} relies on the primary energy sources of an electric power grid. In order to estimate the emitted carbon amount for a manufacturing process, the following equation can be used:

$$CE_{process} = E_{process}\cdot CES \tag{10}$$

In the scope of this study, the theoretical energy consumption prediction model is presented. The amount of carbon emitted by the theoretical energy consumption(CE_{th}) can be found by the following equation [18]:

$$CE_{th} = E_{th}\cdot CES \tag{11}$$

CES can be calculated by the following equation [18]:

$$CES = \eta\cdot(112\cdot\%C + 49\cdot\%NG + 66\cdot\%P) \tag{12}$$

where C, NG and P represent the fractions of coal, natural gas and petroleum, respectively. The coefficients, 112, 49 and 66 represent the amount of carbon emitted per gigajoule of heat released in each case in kilograms and η is the conversion efficiency. The fractions for C, NG and P are 28.9%, 45.4% and 0.2% respectively and they are based on

Turkey's electricity generation by primary resources data presented by Turkish Electricity Transmission Company [19]. With using a common conversion efficiency of 0.34, CES for Turkey can be calculated as 160.85 kg CO_2/GJ.

4 CASE STUDY

A part with three STEP AP224 manufacturing features is designed to demonstrate the developed model. Technical drawing of the case study part is depicted in Figure 4. The stock's size is 200 mm x 250 mm x 40 mm. There are three features to be removed on the stock which are rectangular open pocket, round hole and open slot. The removal process starts with a side milling operation. Then, rough and finish cutting operations for the rectangular open pocket feature are followed, respectively. Same operations for the rectangular open pocket feature are repeated for round hole feature. Ultimately, rough and finish cutting operations for open slot feature take place.

Three different raw materials are used in this study in order to present three design alternatives: Structural Steel (AISI1050), Tool Steel (AISI O2) and Aluminum (6013). Cutters and inserts for milling operations are selected from SECO Tool Catalogues to acquire accurate pragmatic calculations [17]. Nano Turbo R217.69-1010.0-06-2AN cutter and Nano Turbo R217.69-2020.0-06-4AN cutter are chosen as cutters. They have 10 mm and 20 mm cutter diameters, respectively. Inserts are chosen as recommended to be compatible with the cutter and also be applicable with the stock material. For structural steel and tool steel stocks, XOMX060204R-M05F40M inserts and for the aluminum stock XOEX060204R-E03F40M inserts are chosen.

Cutting edge angle (K) is specified by the cutter type. Feed per tooth (f_z) values depend on the chosen cutter, engagement angle (ω_e) and stock material. Width of cut (a_e) and engagement angle (ω_e) values depend on the pathway which the NC-code programmer creates for the operation. Effective rake angle (γ_0) value is the sum of cutter's rake angle and insert's rake angle. Specific cutting energy ($k_c^{1,1}$) and the coefficient m_c rely on the material properties of the stock.

Average chip thickness values are calculated for each manufacturing feature using Equation 9 and theoretical energy consumptions are calculated for each manufacturing feature using Equation 8, as well. Then, theoretical energy consumption amounts are calculated by using Equation 7. Also, the carbon emission amounts computed by using Equation 11. The total theoretical energy amounts consumed for manufacturing the case study part depending on the material of work piece are shown in Table 2. The expanded case study results for each feature and operation are presented in Table 3.

According to the case study results, part which is milled out of an AISI O2 stock consumes highest amount of theoretical energy, AISI 1040 comes next and Aluminum 6013 stock consumes lowest. The carbon emission amount ranking changes correspondingly. Since cutting conditions are assumed as identical for all materials, this theoretical energy consumption prediction results seem to be logical. However, this study does not take account of auxiliary energy consumptions and in order to make more efficient predictions auxiliary energy consumption model is planned as a future work.

Table 2: Case study results.

Material	Eth(kJ)	CEth(g)
AISI 1040	942,97	151,676
AISI O2	1414,26	227,483
Aluminum 6013	419,79	67,523

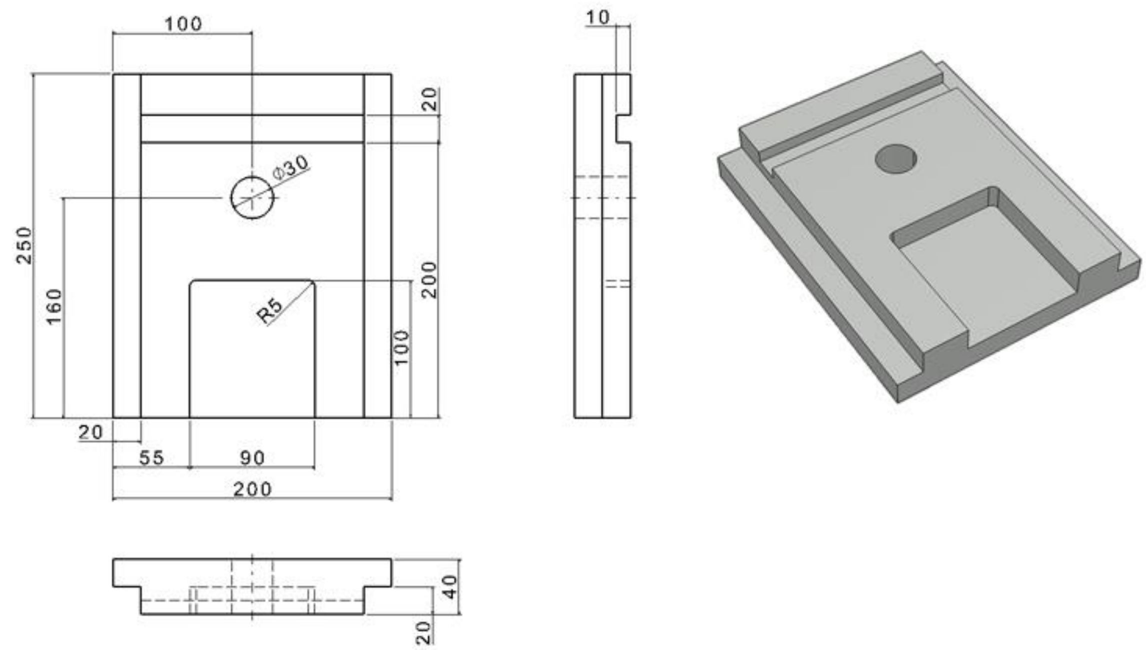


Figure 4: Technical drawing of the case study part.

Table 3: Expanded case study results.

Feature/Op.	Op. Type	Material	hm(mm)	kc(J/mm3)	Vrem(mm3)	Eth(kJ)	CEth(g)
POCKET (Rectangular Open Pocket)	Rough	AISI 1040	0,045	2,775	152000	421,80	67,847
		AISI O2	0,038	4,163	152000	632,74	101,777
		Aluminum 6013	0,051	1,236	152000	187,80	30,207
	Finish	AISI 1040	0,050	2,694	28000	75,45	12,135
		AISI O2	0,043	4,023	28000	112,64	18,119
		Aluminum 6013	0,057	1,197	28000	33,51	5,390
SLOT (Open Slot)	Rough	AISI 1040	0,045	2,775	24000	66,60	10,713
		AISI O2	0,038	4,163	24000	99,91	16,070
		Aluminum 6013	0,051	1,236	24000	29,65	4,770
	Finish	AISI 1040	0,033	2,982	8000	23,86	3,837
		AISI O2	0,029	4,525	8000	36,20	5,823
		Aluminum 6013	0,038	1,335	8000	10,68	1,718
HOLE (Round Hole)	Rough	AISI 1040	0,045	2,775	19634	54,48	8,764
		AISI O2	0,038	4,163	19634	81,73	13,147
		Aluminum 6013	0,051	1,236	19634	24,26	3,902
	Finish	AISI 1040	0,050	2,694	8639	23,28	3,744
		AISI O2	0,043	4,023	8639	34,75	5,590
		Aluminum 6013	0,057	1,197	8639	10,34	1,663
SIDE MILLING	Rough	AISI 1040	0,045	2,775	75000	208,13	33,477
		AISI O2	0,038	4,163	75000	312,21	50,219
		Aluminum 6013	0,051	1,236	75000	92,66	14,905
	Finish	AISI 1040	0,045	2,775	25000	69,38	11,159
		AISI O2	0,038	4,163	25000	104,07	16,740
		Aluminum 6013	0,051	1,236	25000	30,89	4,968

5 CONCLUSION AND FUTURE WORKS

This work aims to develop a methodology which aids engineers to predict energy consumptions and carbon emissions of machining processes at the part design and process planning stage of manufacturing. Utilizing this tool, design engineers can change the cutting conditions and decide between the design alternatives with energy consumption data. By this way, they can not only create more environment-friendly process plans but also decrease environmental impact during manufacturing.

The implementation of the proposed model to CATIA v6 is an ongoing process. Verification of the proposed model by taking measurements from CNC Milling Machine at the Technology Center of TOBB University of Economics and Technology is planned as a future work. Development of a model for predicting auxiliary energy consumption for prismatic parts is also a future work, as well.

6 REFERENCES

[1] International Energy Agency, 2012, World Energy Outlook. Available at : http://www.worldenergyoutlook.org/publications/weo-2012 [Accessed 18 April 2013].

[2] U.S. Energy Information Administration, 2012, Annual Energy Outlook 2012. Available at: http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf [Accessed 18 April 2013].

[3] World Resources Institute, 2005, World Greenhouse Gas Emissions. Available at: http://www.wri.org/chart/world-greenhouse-gas-emissions-2005 [Accessed 18 April 2013].

[4] [4] U.S. Energy Information Administration, 2011, Annual Energy Review 2011. Available at: http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf [Accessed 18 April 2013].

[5] The Intergovernmental Panel on Climate Change, 2007, Climate Change 2007 Mitigation of Climate Change. Available at: http://www.ipcc.ch/pdf/assessment-

report/ar4/wg3/ar4_wg3_full_report.pdf [Accessed 18 April 2013].

[6] International Energy Agency, 2011, G-20 Clean Energy, And Energy Efficiency Deployment and Policy Progress. Available at: http://www.iea.org/publications/freepublications/publication/G20_paper.pdf [Accessed 18 April 2013].

[7] Schey, J.A., 2000, Introduction to Manufacturing Processes, 3rd ed. : McGraw Hill, ch. 16, pp 617-725.

[8] Kalpakjian, S., Schmid, S. R., 2003, Manufacturing Processes for Engineering Materials, 4th ed. Upper Saddle River, NJ: Prentice Hall, ch. 8, pp. 404-504.

[9] Amaitik, S.M., Kılıç, S.E., 2005, STEP-based Feature Modeler for Computer-aided Process Planning, in: International Journal of Production Research, Vol. 43, No. 15, pp. 3087-3101.

[10] Uluer, M. U., Ünver, H. Ö., Akkuş, K., Kılıç. S.E., 2013, A Model for Predicting Theoretical Process Energy Consumption of Rotational Parts using STEP AP224 Features, 20th CIRP International Conference on Life Cycle Engineering, Singapore.

[11] International Standards Organization, 1994, ISO 10303-1 Industrial automation systems and integration - Product data representation and exchange - Part 1: Overview and fundamental principles, Geneva, Switzerland.

[12] International Standards Organization, 2006, ISO 10303-224 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 224: Application Protocol: Mechanical Product Definition for Process Planning Using Machining Feature, Geneva, Switzerland.

[13] Zhao, Y.F. , Habeeb, S., Xu, X., 2008, Research Into Integrated Design and Manufacturing Based on STEP, International Journal of Advanced Manufacturing Technology, Vol. 44, pp. 606-624.

[14] Rahimifard, S., Seow, Y., Childs, T. , 2010, Minimising Embodied Product Energy to Support Energy Efficient Manufacturing, in: CIRP Annals – Manufacturing Technology, Vol. 59, pp. 25-28.

[15] Dahmus, J.B., Gutowski, T.G., 2004, An Environmental Analysis of Machining, Proceedings of the 2004 ASME International Mechanical Engineering Congress and RD&D Exposition, Anaheim, California, USA.

[16] Li, W., Zein, A., Kara, S., Herrmann, C., 2011 An Investigation into Fixed Energy Consumption of Machine Tools, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp. 268-273, Braunschweig, Germany.

[17] SECO Tools, 2012, MN2012 - Milling in: Machining Navigator Catalogue.

[18] Jeswiet, J., Kara, S., 2008, Carbon Emissions and CES™ in Manufacturing, in CIRP Annals – Manufacturing Technology, Vol. 57, pp. 17-20.

[19] Turkish Electricity Transmission Company (TEİAŞ). Available at: http://www.teias.gov.tr/ [Accessed 17 March 2013].

19.6 Cloud SME – Sustainable computer aided engineering for SME´s

César Veiga[1], Luís Rocha[2], Mar Rodriguez[3], David Rodrigues[4]

[1]CESGA - Centro de Supercomputación de Galicia, Santiago de Compostela, Spain
[2]CATIM – Technological Centre for the Metal Working Industry, Porto, Portugal
[3]AIMEN –Centre Tecnologico AIMEN, Porriño, Spain
[4]AIMMAP –Portuguese Association of Metallurgical, Mechanical Engineering and Similar Industrial Companies, Porto, Portugal

Abstract

The authors describes a manufacturing support process, Computer Assisted Engineering (CAE) concept, with a Cloud Computing approach, mainly oriented to SME´s that takes account of manufacturing sustainability in several perspectives such as economic, environmental, innovation and social. This case is a result of the CloudPyme Project (CPP), where the main objective is providing this CAD/CAE tools to SME´s, which in normal cases can´t access to this tools, related to acquisitions issues (e.g. high costs in software, hardware and training).

The concept has been running for providing a structure and services (SaaS), using Cloud Computing, based on Open Source Software (OSS) and support services, given the opportunity to SME´s to improve their products using advanced engineering tools at low price. With this service, small manufacturing companies can design new products in a more efficient way. SME´s using this support service can spend less energy, time, materials and more durable.

Keywords:

Sustainable Manufacturing; Product design, Cloud Computing; SaaS; OSS, CAE;

1 INTRODUCTION

In our days the concept of sustainability meet with general acceptance worldwide and are developed and implemented for a wide range of industries, research, development and manufacturing products. In a competitive and rapidly developing world, producing new and better products in a faster way have huge influence in several sustainable vectors. In future, only companies that develop modern tools and knowledge with an emphasis on sustainability (economic, environment and social) will be continue competitive [1,2,3]. Only those regions and companies that develop modern training concepts with an emphasis on sustainability will be continue to be competitive. Concerning manufacturing processes a great effort must be made to achieve sustainability: e.g. to optimize material consumption given limited resources [1,2,3].

In this context of competitiveness, to make things better and faster, are necessary elements for success. SMEs often do not have the means or resources. These solutions are needed to meet the increasing demands of consumers. The economic importance of sustaining a strong manufacturing industry in Europe is evident. Manufacturing SMEs needs to soak in the knowledge-based economy, which has profound effects on the market, in society and in technology. Young ICT disciplines have progressed rapidly in recent years, allowing users of these technologies the discovery of new working patterns that are contributing to a remarkable progress in this discipline. There is no doubt that the development of tools for CAD/CAE also causes a great impact on manufacturing SMEs that will revolutionize the way they work. Moreover, software is one of the key economic elements in the ICT field, and its structure, competitiveness and industrial applications has the potential to be strongly influenced by open source software [4].

In this paper, a manufacturing support process based on a Computer Assisted Engineering (CAE) concept and a Cloud Computing approach, mainly oriented to SMEs, is described,. It takes into account the manufacturing sustainability in several perspectives such as technologic, economic, environmental, innovation and social. This case is a result of the CPP, where the main objective is to provide these CAD/CAE tools to SME´s, which in normal cases can´t access to them due to acquisitions issues (e.g. high costs in software, hardware and training) [4,5].

The concept has been running for providing a structure, using Cloud Computing paradigm, based on OSS, and support services, given the opportunity to SMEs to improve their products using advanced Engineering tools at low price. With this service, small manufacturing companies can design new products in a more efficient way. SME´s using this support service can spent less energy, time, materials and be more durable [6].

2 MOTIVATION FOR CLOUDPYME PROJECT

Nowadays, manufacturing better products and in shorter time-to-market way, are necessary elements to obtain an entreprise success. The SMEs sometime s hasn't the necessary means neither the resources nor knowledge to achieve these goals. These solutions are necessary to satisfy the every time greater demands of the consumers. The economic importance to sustain a strong manufacturing industry in Europe results evident. The manufacturing SME´s needs to submerge in the knowledge economy based [5,6] that have deep effects in the markets, in the society and in the technology.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5 © Universitätsverlag der TU Berlin 2013

The economic model for OSS is a new approach where what surrounds to the knowledge of code is more important that the code himself. It is based in a distinction between three activities: the development of the software, the services, and the specific developments [6]. OSS creates knowledge around the local companies because it requires a local support, contrary to what occurs with the proprietary software [7].

CPP is a running project for promotion and introduction in manufacturing SMEs of OSS technology for numerical simulation and CAD/CAE through evaluation pilots in Cloud Computing infrastructures, demonstration and evaluation.

The aim of the project is to design, build and test a sustainable infrastructure to support SMEs in the manufacturing sector, to enhance their international competitiveness through the inclusion of free software CAD and CAE to help them design better their products and processes, following:

1. Designing a detailed guide to all the mechanisms, tools and strategies in the short and medium term to obtain maximum efficiency in transferring results, under the free software, CAD / CAE, simulation, the business environment, particularly SME's.

2.Trying develop a model on real experiences with identified companies in the manufacturing sector.

3. Create a superregional infrastructure that supports innovation based on OSS technology transfer, involving regional organizations from different regions that support the generation of knowledge through transfer agents to SME's.

4. Design and implement mechanisms of self-sustainability by establishing conditions to continue the project after the funding period. Analyse based on real experiences and plan the business model to fund infrastructure to self-sustainability of the project.

With the introduction of modern technicians in the manufacturing world, the field has progressed of exponential form in the last decade. These kinds of solutions are necessary to satisfy the every time greater demands of the consumers. The economic importance to sustain a strong manufacturing industry in Europe results evident.

3 OVERVIEW

In order to get the comprehensive overview, a survey was conducted to evaluate the initial situation of CAE usage among SMEs in our Eurozone (Galicia region and North of Portugal) and identify the barriers in the CAE adoption. So, we ran a survey within 109 manufacturing SMEs and were possible retrieve some import information for CPP. Figures 1 and figure 2 shows the main points identified in the CAE adoption. CPP try to dismiss some of those identified barriers:

- The companies have a constant need of training in commercial tools.
- The companies are using or interested in CAD/CAE tools.
- High interest in simulation of processes of manufacture in SME's. However, there is not detected any free software that can run this type of simulations. It is a potential future opportunity of business to take into account.
- Several companies have needs of use these tools, but do not have the sufficient level of business to justify the purchase of commercial licenses.
- The exchange file formats mostly used are STEP and IGES.
- Given the level of implantation, the decision is that does not promote the CAD tools and the project will focus in CAE tools.
- It is necessary to offer alternatives that improve the commercial solutions, proposing feature that are not available in the commercial software or using these features with commercial software is expensive or time consuming.

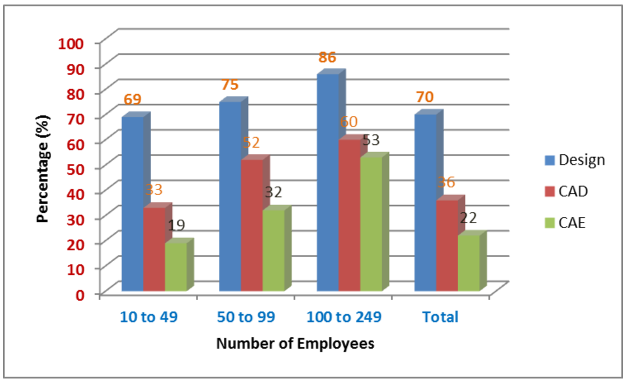


Figure 1: Uses of software in SMEs

All those figures reassure similar analysis and conclusions done previously [8,9]. From data collected and analyzed, it was possible extract the following conclusions and project recommendations with the aim to improve the current situation of the manufacturing SMEs of the target region:

- A high percentage (80 %) of the SMEs polled already uses CAD tools.

So the recommendation is to boost the use of the CAD with OSS on 20% that does not use. Analyze with the group of companies that have answered to polls and its parameters: type of uses (2D), degree of confidence in the tools used, to establish mechanisms of the adoption of new solutions and uses OSS.

- The majority of companies (70%) the types of simulation and calculation processes realized are for Mechanical or Structural calculations.

So the recommendation for the project is to include Salome-Mecca like one of the packages for the pilots.

- An important part (55 %) of the SME's uses the results obtained with the CAD in applications of CAE tools.

So the recommendation is to promote the execution of actions for promoting new operative like the use of parametric analyses.

- The use of commercial software CAE is of majority of use (15 companies) comparing of the free software.

So the recommendation is to execute specify actions of promotion/diffusion, based in the successful marry that it has to generate the project.

- A significant percentage of companies (73%) that have training needs; a 60% needs CAD/CAE integration processes in the company.

So the recommendation was to design and spread courses of specific training; looking for solutions OSS for integration PLM and it´s an opportunity of business (business plan).

- Only a small percentage of companies use internal developments.
- There is a significant percentage (27%) that needs custom developments.

So the recommendation is to use it like an opportunity and boost the creation of infrastructures of an auto-sustainable support in based on spin-offs or new initiatives.

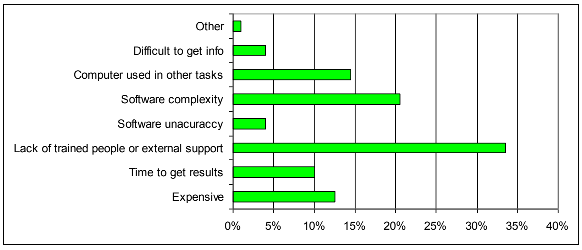


Figure 2: Identified Barriers and Adoption Constraints from CAE users.

4 THE PROJECT

The purpose of CPP is to promote and evaluate the introduction of the emerged advanced technologies such as cloud computing, Virtualized Desktops, virtualization, Open Source CAE, service-oriented technologies, advanced computing technologies into existing advanced manufacturing models and enterprise information technologies. The concept, architecture, core enabling technologies, and typical characteristics of CPP are developed and investigated. A service platform has been developed and deployed.

This evolving technology is driving manufacturing organizations to evolve from traditional approaches towards new models and paradigms that facilitate agile fulfilling of customer requirements [10]. This new scenario requires new patterns organizations of production, more dynamic and flexible, which can adapt flexibly to the changes occurring in the environment due to market demand [7], [10], [11] without causing a major impact on the final costs of the products.

The project was planned and driven throw several operational stages (figure 3) from getting the initial situation until defining a new business model.

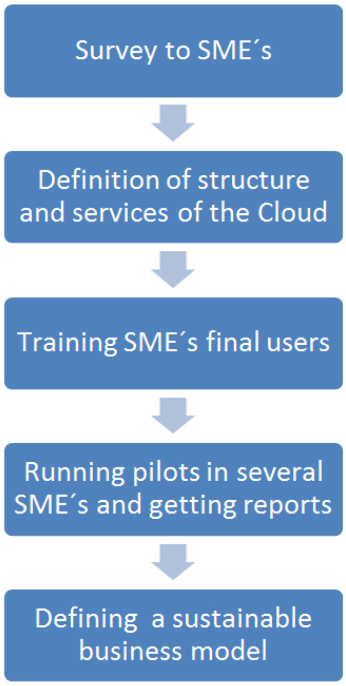


Figure. 3: CloudPyme project operational phases

Operationally a support infrastructure and a computational infrastructure were designed to provide value added services for manufacturing SME's CAE tools based on OSS. This infrastructure has been tested through pilots within SME companies.

Computational infrastructure is based on three fundamental components (Fig. 4):

- The user distribution,
- The front-end portal service
- The back-end infrastructure

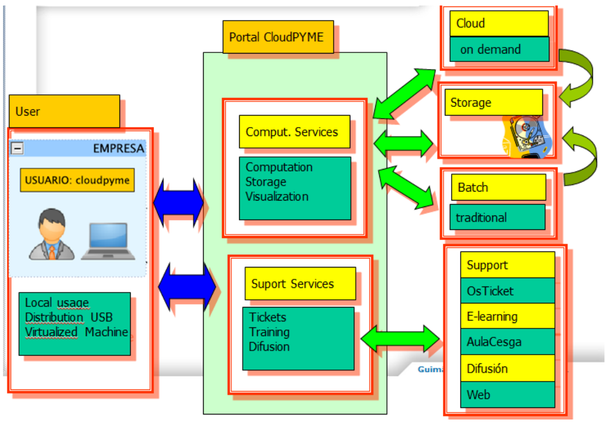


Figure 4 – Diagram of the overall architecture of the service

The user component is based on an operating system image that can be downloaded to a local disk to boot from any computer user who wants to connect to the platform. And somewhat like a CAE generated in Linux is based on a Linux operating system, specifically Centos [12]. The user, each

SME that embrace the project, can download the image to run in a local computer as a whole distribution (similar to CAELinux, or execute the distribution as a virtualized service).

In such distribution have different products initially installed open source software such as SALOME 6.4.0 [13], CodeAster 10.6 (http://www.code-aster.org) [14], Salome_Meca 2012.1 (www.salome-platform.org) [13], other packages are in the process of integration, such as computational fluid dynamics software (CFD) OpenFoam (www.openfoam.com) [15].

After the initial evaluation the selection was to SALOME which is an OSS that provides a generic platform for Pre and Post Processing for numerical simulation. It is based on an open and flexible architecture made of reusable components. Is a cross-platform solution, and distributed as open-source software under the terms of the GNU LGPL license, the other software was Code_Aster, beyond the standard functionalities of a finite elements software for solid mechanics, Code_Aster uses numerical models from specific research works designed to solve these issues, which enables the control of their implementation and a quick transfer to engineering studies. Code_Aster (figure 6) has the availability of a powerful, robust and stable simulation software for engineering studies (about 200 users in-house and thousands as “free” users), used with quality assurance requirements. Constantly developed, updated and upgraded with new models, Code Aster contains more than 1.200.000 lines of source code, mostly in FORTRAN and Python.

Also been integrated into the distribution for the user (figure 5) a series of features such as Connection, Storage, Portal, or DEMO kit, allowing users to access this features from a local computer, in any of the companies participating in CPP, using the cloud infrastructure by remote access.

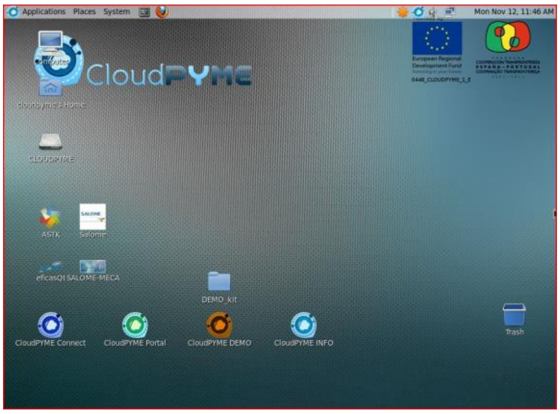


Figure. 5. User interface of the User-distribution.

Downloading was also virtualized and run it as a service managed in virtual machines (as VirtualBox).

The second component is the front-end level CPP is a service logic layer, where they are clearly different computing services and support services. Fig. 7 shows a screenshot of the main portal, with three main features support, resource management and documentation.

Computational services include storage, visualization and computational services. Simulations can be executed in a double way according to a batch system or cloud model) both execution modes share the same file system.

Support services are organized in support services (ticketing), training (aulacesga - http://aula.cesga.es) and dissemination (project website – www.cloudpyme.eu).

The back-end services are developed in the CESGA infrastructure has made available to the project.

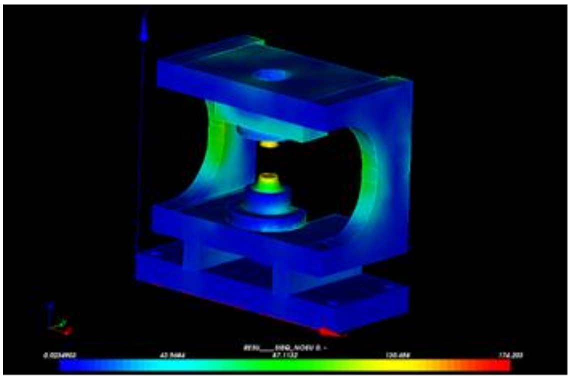


Figure 6 – Code-Aster simulation case

5 SUSTAINABLE VECTORS

The implementation and dissemination of simulation tools allows reducing the costs of the development and future production. The product modeling by Cloud Computing and supported by a service, allows better refinement in the prototyping phase, before doing the process of manufacturing. For example, it allows simulating mechanical simulations allowing saving material and less produce prototypes for real experiments reducing time in laboratory tests, so the model of computation allows saving time, energy and material. With these focus we can identify gains in the three vectors of sustainability [16]: This paradigm is based on the Internet and especially the concept of Cloud Computing. To ensure the practical feasibility of the proposal, the work has been developed using the concept of Software as SaaS. SaaS allows us to offer resources of element of production and manufacturing processes through agile manufacturing using CAE accessible in the Cloud.

SaaS enables us to overcome the technological and conceptual gap between the plant level and management level through service oriented architectures.

•Environmental sustainability: Using less material and less energy during development and production, we will contribute to preserving nature and the environment.

•Economic sustainability: The implementation and dissemination of simulation tools allows reducing the costs of production. The product modeling by Cloud Computing allows better refinement in the prototyping phase, before doing the process of manufacturing. For example, it allows simulating chemical and biochemical reactions to plan the result of the experiments reducing at least the time in laboratory, so the model of computation allows saving time, energy and material.

•Social sustainability: This approach can increases equality of opportunity when it comes to accessing to CAE tools. SMEs and their technicians and engineers, for example, in new micro manufacturing companies, that do not have means to access to ultimate CAE tools, with this kind of technology, micro and small companies have the same opportunity to use engineering tools like medium and big enterprises.

Maximize Flexibility; the fluctuating demand of computing resources is a reality enterprises of varied sizes face every day. Scaling the hardware capacity to meet peaks can avoid the potentially lead to unused resources and increased cost.

Compute Everywhere. CPP provides immediate access to high performance computing for product innovation. The web based user interface is accessible from a variety of different platforms; hence, project workloads can be uploaded, submitted, monitored and reviewed anytime, anywhere.

Drive Innovation. CPP offers efficient and innovative solutions for optimization, completely out-of-the-box. Pushing workloads to an HPC cloud has never been easier: users can generate the model on their desktop, upload their data infrastructure and quickly obtain their results.

Fig. 7 CloudPYME Portal of services.

Dedicated and Secure. Whether an enterprise wants to integrate the computing resources or solely rely on cloud computing, security is always a priority. CPP offers secure access to dedicated computing nodes, creating an independent environment for each customer.

6 FUTURE DEVELOPMENTS

This is an ambitious work that is at an early stage, so many questions both conceptual and applied must be solved. We are currently developing the layers described. We use a complete use case and close to the real problems of the industry so that it can serve as validation and, above all, to provide the necessary feedback to refine and adjust the concepts that are being defined.

We intend develop an economic sustainable structure that will allow continue providing these services to SMEs, by creating an adaptable business model that will take some income from the who used the service on the current project. The next step is plan add more CAE applications in CPP and associated services, providing different simulation environments like Computational Electromagnetics (CEM) and Computational Fluid Dynamics (CFD) software´s. As described before, during the project, pilot SME's tested the system by development there's own project using the provided software, training phase and distance support service. At the end the users of these companies report their experience by giving feedback about several vectors like usability, importance, and suggestions.

Continue testing and improve the all service with a larger number of SMEs, and from several manufacturing environments. Another issue is the dissemination of the project, by showing the advantages and analyzes possible auto-sustainability mechanisms as spin-off opportunities or other sustainable options.

7 CONCLUSIONS

In this paper we have presented a new manufacturing scenario called CloudPYME. The systems developed under this paradigm provide significant benefits for manufacturers who need to deploy agile manufacturing model.

Simulation processes is a growing need for SME's and directly linked to a sustainable manufacturing activity. The economic model for free software is a new approach where the knowledge surrounding the code is more important than the code itself. It is based on a distinction between three activities: the development of software, services, and specific developments. Since the software is free, the latter two activities must finance the first. OSS creates knowledge about local businesses because it requires local support, contrary to what happens with proprietary software. There is much knowledge and tools available free software, developed in research projects for years. The consortium has covered the entire spectrum of agents required (research centres, transfer agents, public sector, etc.). And the partners have already undertaken similar projects at a regional level much less ambitious (analysis and selection of tools).

There is an opportunity for:

• Creating an innovation process for SMEs.

• Location and identification of knowledge shared by the regions.

• Managing the transition to a knowledge-based economy, a key challenge right now for the European Union.

• Ensure a competitive and dynamic economy with more and better skilled jobs, and a higher level of social cohesion.

In the current frame of competitiveness, manufacturing better products and in a faster way, are necessary elements to obtain a success enterprise. The economic importance to sustain a strong manufacturing industry in Europe results evident. The manufacturing SME´s needs to submerge in the knowledge based economy that has deep effects in the markets, in the society and in the technology.

In the European Union, SME's provide two out of three of private sector jobs and contribute to more than half of the total value-added created by businesses. Dynamic SME's are also important for innovation in manufacturing and services. With nine out of ten SMEs in Europe with less than ten employees, SMEs often face greater obstacles than bigger firms in terms of skills, costs of resources, funding or access to markets [16].

One of the main challenges for the sustainability of the EU economy and the generation of new jobs and revenues is to support SMEs' competitiveness by helping them produce better products, reduce the time and the cost of design and production and thus develop high-value products and high-tech skills. This will lead to development of existing industries as well as the emergence of high-tech and innovative companies. Technology transfer between academia and industry also has to be encouraged, as a key aspect of the innovative products and services design [17].

8 ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the European Union in the Operational Programme for Cross-border Cooperation: Spain – Portugal (POCTEP) through the project 0448_CLOUDPYME_1_E. The authors gratefully appreciate the technical assistance of the companies SMEs that have participate in the pilot experiences for their contribution.

The project results would not have been possible without funding from the European Commission, Spanish and Portuguese govern. This paper reflects the perspectives and experience of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

9 REFERENCES

[1] F. Jovane, H. Yoshikawa, L. Alting, C. Boe¨, E. Westkamper, D. Williams, M. Tseng, G. Seliger, A. Paci, 2008, The incoming global technological and industrial revolution towards competitive sustainable manufacturing, Manufacturing Technology, CIRP Annals (57): 641–659

[2] E. Westkämper, 2006, Digital Manufacturing in the global Era, 3rd International CIRP Seminar Digital Enterprise Technology, Setúbal, Portugal.

[3] Y. Korena, U. Heiselb, F. Jovanec, T. Moriwakid, G. Pritschowb, G. Ulsoya, H. Van Brussele, 1999, Reconfigurable Manufacturing Systems, CIRP Annals - Manufacturing Technology (48), Issue 2, 527–540

[4] Lerner, Josh and Jean Tirole. "The Economics Of Technology Sharing: Open Source and Beyond," Journal of Economic Perspectives, 2005, v19 , n. 2: 99-120

[5] Moch, R., Merkel, A., Günther L., Müller, E., 2011,The dimension of innovation in SME networks? a case study on Cloud Computing and Web 2.0 technologies in a textile manufacturing network, International Journal of Innovation and Sustainable Development, Volume 5: 185-198

[6] Research Results for SMEs – V, 2004, SMEs in the Fifth Framework Programme, ISBSN 92-894-5038-X

[7] R. Ghosh, 2007, Study on the: Economic impact of open source software on innovation and the competitiveness of the Information and Communication Technologies (ICT) sector in the EU, ENU-MERIT.

[8] J. Kennedy, P. Hyland, , 2003, A comparison of manufactoring technology adoption in SMEs and large companies, 16th Annual Conference of Small Enterprise Association of Australia and New Zealand.

[9] P. Quintela, A. Fernández, A. Martínez, G. Parente, M. Sánchez, 2012, i-MATH Map of Demand for Mathematical Technology (TransMATH Demand Map), TransMath. Sxi , Springer for Innovation , Volume 1, 7-44

[10] F, Tao; L Zhang, VC Venkatesh, YL Luo, Y Cheng, 2011, Cloud manufacturing: a computing and service-oriented manufacturing model. Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture.

[11] A. Gunasakaran, 1999, Agile manufacturing: A framework for research and development. International Journal of Producting Economics, Vol. 62, Issues 1-2, pp. 87-105.

[12] C. Negus, T. Boronczyk, 2009, CentOS Bible, Wiley Publishing, ISBN:047048165X 9780470481653

[13] D. Caruge and L. Dada, 2005, The SALOME Open Source CAE platform: application to reactor physics simulation, Seminar ESA “Integrated Open CAD/CAE Platforms for Mechanical Engineering", Netherlands.

[14] J. Proix, N. Laurent, P. Hemon, G. Bertrand. Code Aster, manuel de référence. Fascicule R, 8. Code Aster.

[15] M. Beaudoin, B. Gschaider, 2008, The OpenFOAM-extend project on SourceForge: current status. Presented at the 3rd OpenFOAM Workshop, Milano, Italy.

[16] Antonio A., Mata, T., Costa, C, and Sikdar, S.,Framework for Sustainability Metrics. 2007, Ind. Eng.Chem. Res., Vol. 46, pp. 2962-2973.

[17] S. Mayer, W. Blaas, 2002, Technology Transfer: An Opportunity for Small Open Economies, The Journal of Technology Transfer, Volume 27, Issue 3, 275-289

GCSM
11th Global Conference on Sustainable Manufacturing
2013
23rd - 25th September
Berlin - Germany

19.7 Reducing the cumulative energy demand of technical Product-Service Systems

C. Bohr[1], S. Waltemode[1], J.C. Aurich[1]

[1] Institute for Manufacturing Technology and Production Systems, University of Kaiserslautern, Germany

Abstract

Technical Product-Service Systems (PSS) are made up of a technical product enhanced along its lifecycle by different services. PSS have a high potential to increase the energy efficiency within the capital goods industry. In order exploit these potential systematically, a method to analyze and reduce the cumulative energy demand (CED) of PSS is required. However, the existing guideline for calculating the CED is mainly intended to physical products. It neglects the services shares of a PSS as well as the interdependencies between products and services. Against this background, this paper provides a research approach that aims at calculating, analyzing, and reducing the CED of PSS.

Keywords:

Product-Service System, Cumulative Energy Demand, Lifecycle Engineering

1 INTRODUCTION

Manufacturers of capital goods no longer produce and offer only pure technical products. They offer technical Product-Service Systems (PSS). While in the past offering services was a possibility to differentiate in competition, nowadays offering a technical product and several services is almost common practice in capital goods industry [1].

The increasing responsibility of companies for a sustainable use of resources requires an approach that calculates, analyzes, and reduces the cumulative energy demand (CED) of a PSS. The guideline VDI 4600 provides an approach to determine the CED of technical products [2]. The guideline also pretends the target to determine the CED of services. However, the guideline does not address the special characteristics of services like intangibility, simultaneity of production and consumption and perishability of services [3]. But, these are the requirements to determine the CED of services. Regarding the analyses and the reduction of the CED of PSS, dependencies and influencing factors between PSS components are also required and not addressed in the guideline.

Therefore, in this paper a new approach is presented, that is based on the guideline VDI 4600 and that is extended in the manner to calculate, to analyze, and to reduce the CED of PSS.

2 TECHNICAL PRODUCT-SERVICE SYSTEMS

Technical Product-Service Systems (PSS) are customer individual solutions that consist of a technical product that is supported and enhanced during its lifecycle by different services [4, 5, 6]. The following types of services are typically part of a PSS [7]:

- Technical services (e. g. maintenance) aim at ensuring the functionality of the technical product.
- Qualifying services (e. g. operator trainings) aim at improving the qualification of the operator.
- Process-oriented services (e. g. application improvement) aim at improving the production processes of the customer.
- Logistical, information-providing and financial services (e. g. spare part supply, product information and leasing) aim at supporting the customer's company.

Moreover, end-of-life services (e.g. remanufacturing) have to be mentioned that aim at recycling or disposing of a technical products or single product components.

From a system-oriented point of view PSS can be modeled with the three sub-systems "technical product", service network", and "customer" (Figure 1). Each sub-system contains different resources which are necessary for the PSS delivery process. The sub-system "technical product" contains the technical product of a PSS that can be described by the product structure. The sub-system "service network" includes the resources for delivering the services (e.g. service vehicles, service technicians, and tools). The sub-system "customer" comprehends the operating personal of the customer as well as further resources regarding the usage of the technical product.

G. Seliger (Ed.), Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions
ISBN 978-3-7983-2609-5

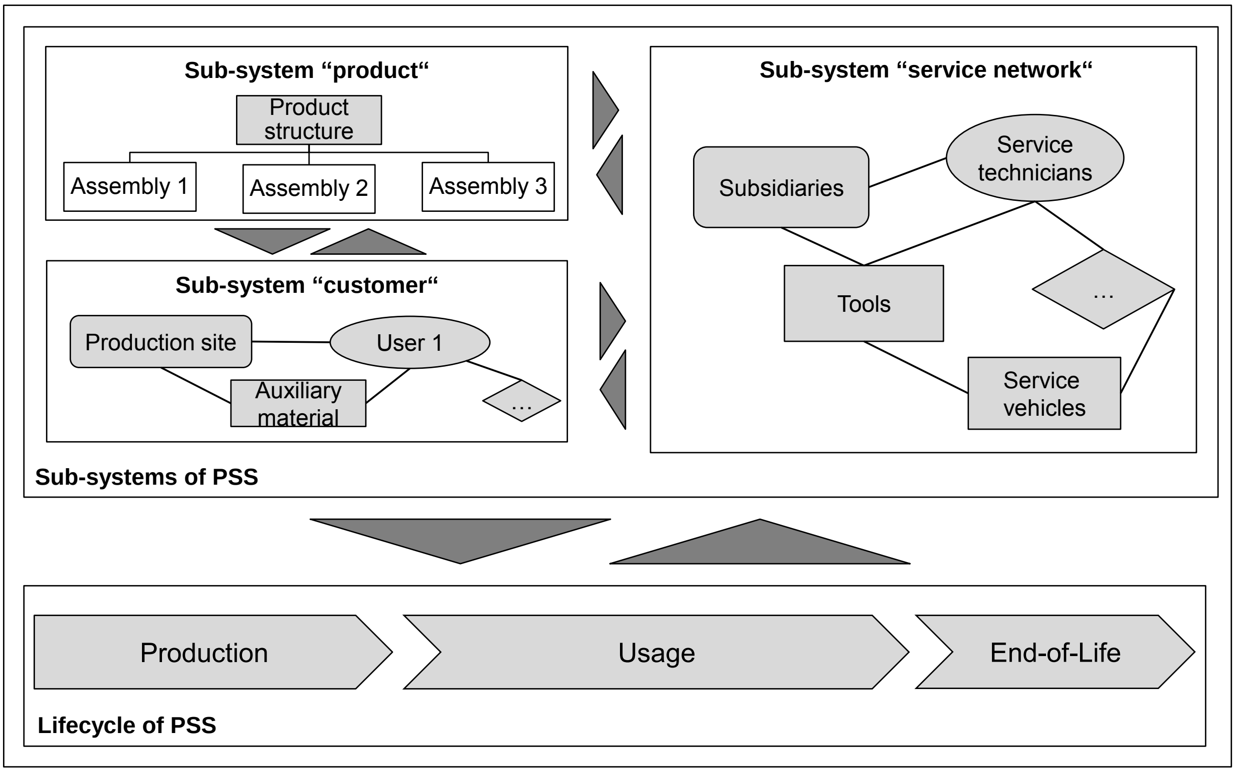


Figure 1: PSS from a system-oriented and a process-oriented point of view (following [8]).

From a process-oriented point of view the PSS lifecycle starts with the production of the technical product and the acquisition of the service resources, followed by the usage of the technical product by the customer including service delivery, and the end of life. In the literature, there is a common understanding that these services can be described by the three dimension potential, process, and result [9]. This representation of PSS from a system-oriented and a process-oriented view builds the basis for PSS assessments regarding different target figures.

While numerous research activities are dealing with economic benefits of PSS (e.g. Lifecycle Costing), the initial goal of PSS research was to reduce consumption of resources by different business models as well as by the delivery of different services [10, 11].

3 CUMULATIVE ENERGY DEMAND (CED)

In the guideline VDI 4600 a procedure is presented to determine the CED by addressing the production, the usage, and the disposal of an economic good. So, the CED in the guideline represents the sum of the cumulative energy demands for the production (CED_P), for the usage (CED_U) and for the disposal (CED_D) of a technical product. It has to be indicated for these partial sums which preliminary and parallel stages are included [2].

Furthermore, primary energy is defined as energy content of energy carriers that are found in nature and have not yet been converted through technical means. The CED denotes the sum of the cumulative energy consumption (CEC) and the cumulative non-energy demand (CND). The CED includes all the final energies for heat, energy, light, and other forms of effective electricity generation handled and valued as primary energy using overall efficiencies of supply. The CND is the sum of the energy content of all energy carriers employed for non-energy purposes and the inherent energy of working materials, valued as primary energy [2].

However, to determine the CED of a PSS, in the guideline 4600 is missing the energy demand. In particular, the service delivery processes is not considered appropriately.

3.1 CED of technical products

The CED of a technical product represents the sum of the cumulative energy demands for the production (CED_P), for the usage (CED_U), and for the end-of-life (CED_E) of objects.

- CED_P denotes the sum of those energy expenditures valued as primary energy which results from the production of an object itself as well as from the acquisition, processing, fabrication and disposal of the production auxiliary, materials, the consumables and the production facilities including the demands for transport [2].
- CED_U denotes the sum of those energy expenditures valued as primary energy which result from the usage of the technical product. In addition to the energy consumption for operation itself, this sum also includes the CED for the production and disposal of spare parts, auxiliary materials and consumables, as well as of production facilities which are required for operation. The energy demand for transports is to be included [2].
- CED_E is the sum of those energy expenditures valued as primary energy which result from the recycling

(CED_R) and the disposal (CED_D) of an object or of parts of the object. This sum includes in addition to the energy use for the recycling and for the disposal itself the CED for the production and the disposal of auxiliary, materials and consumables as well as of production facilities which are required for the recycling and for the disposal. The energy demand for transports is to be included. Furthermore, CED_R is differentiated into the material and the energetic recycling. The material recycling regards the separation and the renewed use of materials. The energetic recycling is the use of the object or parts of the object as energy source for energy production.

The important foundation for the calculation of the CED of a technical product is the unambiguous definition of the balancing boundaries. The balancing boundary extends from the raw material at its original deposit to the final storage or deposit of all materials or substances, where the diffuse release into air, water, and soil also have to be taken into account. The material and energy flows crossing the boundaries are to be defined and quantified exactly. The boundary setting is carried out according to local, temporal and technological criteria [2].

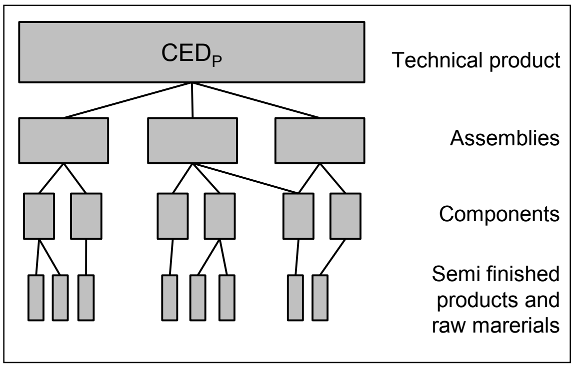


Figure 2: Material tree for the CED of production [2].

To determine the CED_P it is necessary to define the material tree for a production process (Figure 2). In this tree, the levels of production as well as the system boundaries are depicted. In the analysis of the product composition a tree structure in the direction opposite to the course of production is obtained which ramifies into further branches after each stage. Each ramification then constitutes an individual energy balance space. Starting with the final technical product, for each partial flow of the production process the energy consumption is examined [2].

To estimate the CED_U it is necessary to define the process-chain in the use phase of the technical product. The several processes in the process-chain can be seen as the system boundaries. Each process then constitutes an individual energy balance space. The process-chain can be divided into main-processes and sub-processes which have to be combined to the process-chain (Figure 3).

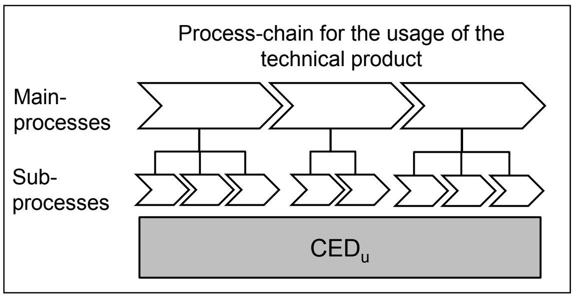


Figure 3: Process-chain for the CED in the use phase.

3.2 CED of services

The CED of services differentiates from the CED of technical products because of the special characteristics of services. The calculation of the CED of services is not pointed out in guideline VDI 4600. Services are intangible and are typically produced and consumed at the same time [9]. Furthermore, the potential, process, and result dimensions of services have to be considered (Figure 4).

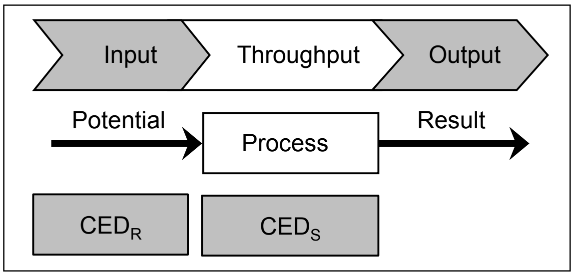


Figure 4: CED of services.

Therefore, the CED of services represents the sum of the cumulative energy demand to provide resources for the potential dimension (CED_R) and the cumulative energy demand for the service delivery (CED_S):

- CED_R denotes the sum of those energy expenditures valued as primary energy which result from the production of the resources itself as well as from the acquisition, processing, fabrication and disposal of the resources including the demands for transport.
- CED_S denotes the sum of those energy expenditures valued as primary energy which result from the process of service delivery itself.

As well as for technical products, the definition of the balancing boundaries is an important foundation for calculating the CED of services.

3.3 CED of PSS

The CED of a PSS indicates the entire demand, valued as primary energy, which arises over the whole PSS lifecycle. It consists of the sum of the cumulative energy demands for the production of the physical product (CED_P), for the provision of service resources (CED_R), for the usage of the product (CED_U), for the process of service delivery (CED_S) and for the end-of-life of the technical product (CED_E) (Figure 5).

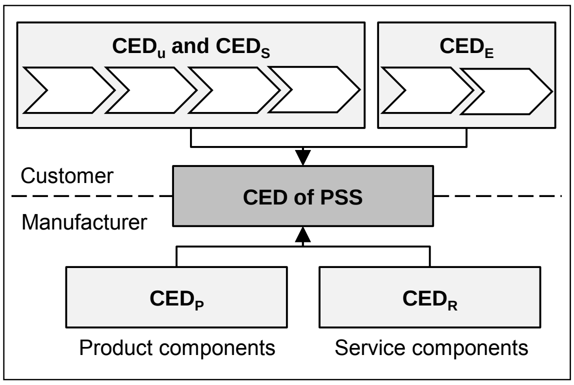


Figure 5: CED of PSS.

4 FRAMEWORK FOR REDUCING THE CED OF PSS

In this section a framework is presented that aims at analyzing and reducing the CED of PSS (Figure 5).

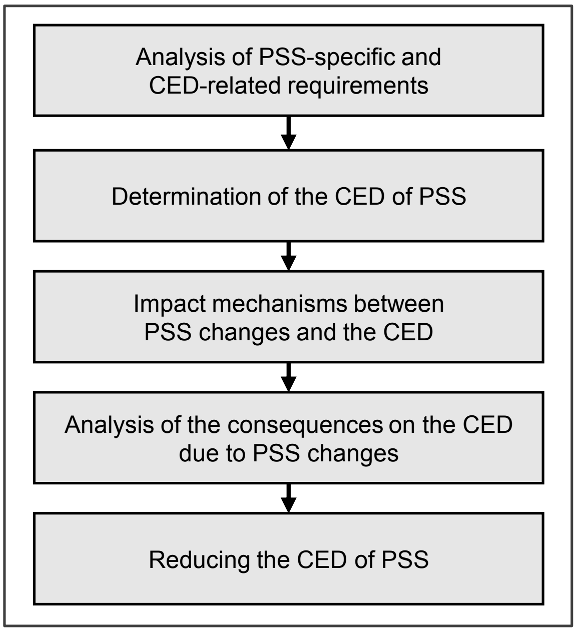


Figure 5: Framework for reducing the CED of PSS.

The first step contains the analysis of a specific PSS. PSS components as items of the balance-sheet, the PSS lifecycle and dependencies between PSS components have to be analyzed and defined. The second step comprehends the determination of the CED of the specific PSS with a process chain analysis. In the third step, a definition of impact mechanisms between PSS changes and the CED has to be done, which build the basis for an analysis of the effects of PSS changes on the CED (step four). Finally, control levers to reduce the CED of the specific PSS have to be identified. In the following, each of the steps will be presented in more detail.

4.1 Analysis of PSS-specific and CED-related requirements

First, the considered PSS has to be described textually. Afterwards, the CED relevant PSS components have to be identified. This contains a process oriented description of the PSS components. PSS components are the physical components of the product, the several services represented by their resources and delivery processes, the operation processes in the use phase of the PSS and the end-of-life processes of the PSS.

Besides the process-oriented modeling of the PSS components, mutual dependencies and interactions between them, have to be described. For this reason, the PSS components shall be compared pairwise. After that, the description of the dependencies of PSS components takes place, with regard to those attributes, which are relevant in the context of the CED. These dependencies and interactions have to be described as CED relevant influencing factors. For example, the interaction between the fuel consumption of an engine as a product component and the service “driver training for an optimal affliction of the engine” could be a CED relevant influencing factor. Subsequently, the described dependencies have to be structured and classified.

4.2 Determination of the CED of PSS

In this part of the framework, the CED has to be determined in the manner which is described in chapter 3.3. Therefore, the balancing boundary and the items of the balance-sheet for the determination of the CED have to be figured out. The balancing boundary of a PSS should be focused on the usage of the PSS, the production of the technical product and the provision of the service resources. For example, the CED of raw materials at its original deposit is not considered within this approach.

The determination of the CED has to be done with a process chain analysis of the PSS components. Therefore, it has to be assigned to every process-oriented described PSS component, the specific CED data. This specific CED data is the energy demand, which arises in connection with the execution of the process. Finally, the CED of the PSS can be determined by combining the boundary settings, carried out according to local, temporal and technological criteria.

4.3 Impact mechanisms between PSS changes and the CED

In this step, impact mechanisms have to be defined. Impact mechanisms describe the effects of changes of PSS components on the CED of the PSS.

First, CED relevant changes of PSS components have to be identified on the basis of the influencing factors identified in the first step. These PSS changes have to be classified. Furthermore, cause-and-effect-relations between PSS changes and the CED have to be derived. This could be done in general terms with if-then-schemes.

Afterwards, the derived cause-and-effect-relations have to be translated in generalized impact mechanisms. This takes place with the help of event-driven process chains (EPC) [12]. Even so, the classified PSS changes represent the first triggering events within the process chain. Furthermore, CED relevant input and output variables, functions and logical operators within the process chain have to be defined. Additionally, CED relevant information of the influencing factors has to be derived. For example, CED relevant information may be the optimal engine speed for fuel-efficiency.

4.4 Analysis of the consequences on the CED due to PSS changes

In the fourth step, effects on the CED due to PSS changes will be analyzed. Therefore, CED relevant PSS components have to be linked with the impact mechanisms. This enables a quick and target-oriented identification of impact mechanisms which are relevant for the analysis of the consequences on the CED due to PSS changes. For analyzing the consequences, a procedure has to be processed which takes place in four steps (Figure 6).

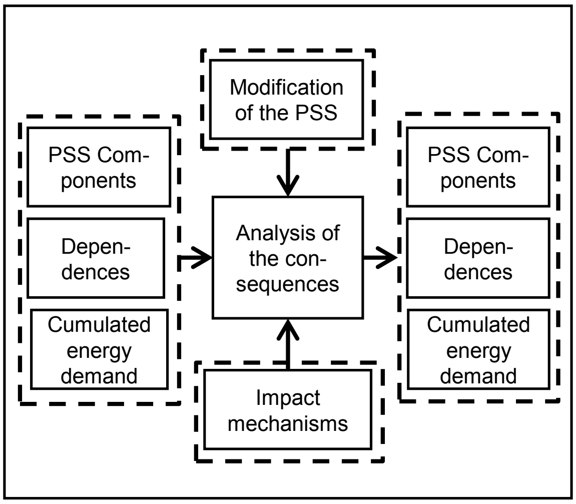


Figure 6: Analysis of consequences on the CED.

First, CED relevant PSS components and also their dependencies among themselves have to be transferred in a model. Second, the CED for this model has to be determined. Afterwards, potential PSS changes are suggested (e.g. the extension of maintenance intervals). Due to the defined impact mechanisms and an appropriate information base, it is possible to derive a modified PSS with a changed CED. Finally, a comparison to the initial situation between the changed PSS and the changed CED could be analyzed.

4.5 Reducing the CED of PSS

In the fifth step, control levers to reduce the CED of PSS have to be identified and implemented. The identification of CED reducing control levers is based on the previously defined CED relevant influencing factors (step 1) and defined CED relevant PSS changes (step 3). Within the influencing factors and the PSS changes, levers have to be identified, which support the reduction of the CED of the entire PSS. The identified levers have to be described and classified. Afterwards, the CED reducing control levers have to be implemented in the impact mechanisms, which are defined in part four of the framework (Figure 7). This builds the basis for the development of a rule-based procedure, which has to be passed for a systematic reduction of the CED.

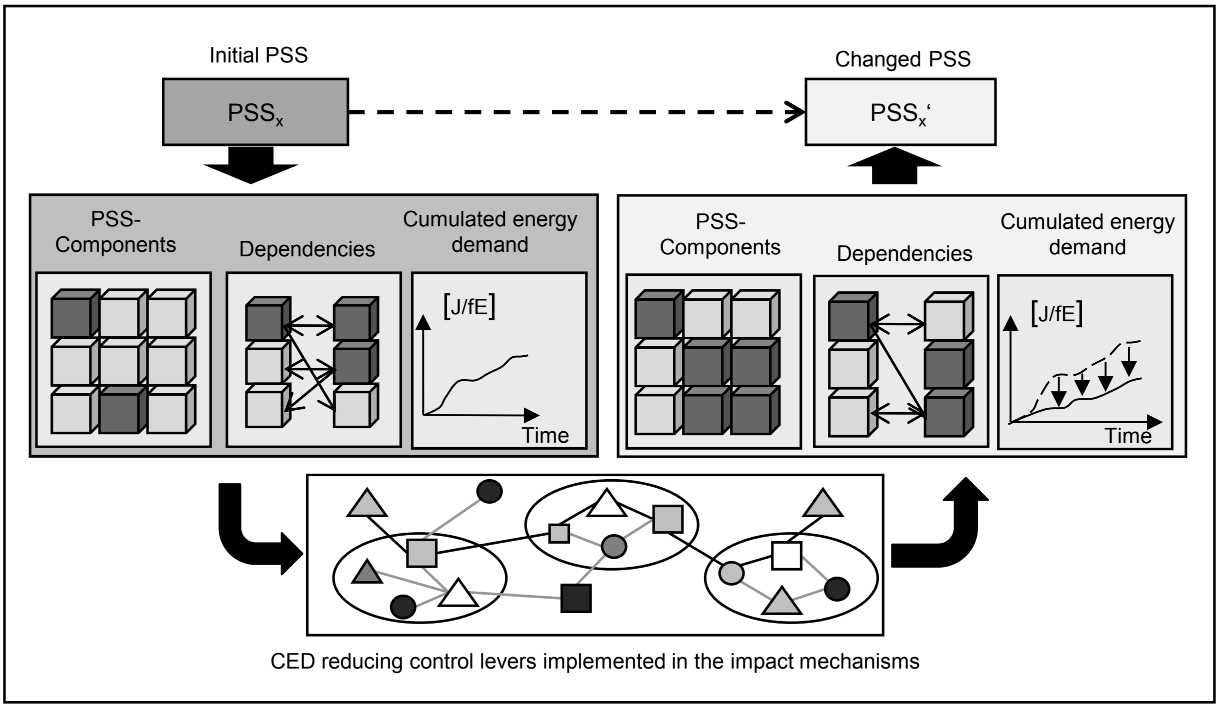


Figure 7: Approach to reduce the CED of PSS.

5 SUMMARY

Existing approaches for calculating the CED refer to physical products and do not consider services or PSS appropriately. Within this paper an approach was presented that aims at calculating, analyzing, and reducing the CED of PSS. At first, a concept was introduced to consider the service shares of a PSS when calculating the CED. Thus, the overall CED of a PSS can be calculated by summing up the CEDs of the production of the technical product, of the provision of service resources, of the usage of the technical product, of the process of service delivery, and of the end-of-life of the technical product. This builds the basis for a framework for analyzing and reducing the CED of PSS. It comprehends four main phases and results in a rule-based procedure, which has to be passed for a systematic reduction of the CED. In the future, this framework has to be specified and validated with different use cases from the capital goods industry.

6 ACKNOWLEDGEMENT

The presented results are partially part of the ongoing project InnoProm-project “Productivity and quality of services” co-funded by the European Funds for Regional Development (EFRE) and the German state Rhineland-Palatinate.

Wachstum durch Innovation – EFRE

RheinlandPfalz

Diese Veröffentlichung wurde von der Europäischen Union aus dem Europäischen Fonds für regionale Entwicklung und vom Land Rheinland-Pfalz kofinanziert.

7 REFERENCES

[1] Waltemode, S., Mannweiler, C., Aurich, J.C., 2012, Life Cycle oriented Quality Assessment of technical Product-Service Systems. In: Dornfeld, D.; Linke, B. (ed.): Leveraging Technology for a Sustainable World, Proceedings of the 19th CIRP Conference on Life Cycle Engineering, 23-25 May, Berkeley, USA: 49-54.

[2] VDI, 2012, VDI guideline 4600: Cumulative energy demand.

[3] Zeithaml, V.A., Bitner, M.J., 2000, Services Marketing – Integrating Customer Focus across the Firm, Second edition, McGraw-Hill, Boston.

[4] Meier, H., Roy, R., Seliger, G., 2010, Industrial Product-Service Systems – IPS², CIRP Annals – Manufacturing Technology, 59/2: 607-627.

[5] Aurich, J.C., Fuchs, C., 2006 Wagenknecht, C.:Life cycle oriented design of technical Product-Service Systems, Journal of Cleaner Production, 14/17: 1480-1494.

[6] Baines, T.S., et al, 2007, State-of-the-art in Product-Service Systems, Journal of Engineering Manufacture, 221:1543-1552.

[7] Aurich, J.C., Mannweiler, C., Schweitzer, E., 2010, How to design and offer service successfully, CIRP Journal of Manufacturing Science and Technology, 2/3:136-143.

[8] Fuchs, C., 2007, Life Cycle Management investiver Produkt-Service Systeme – Konzept zur lebenszyklusorientierten Gestaltung und Realisierung. Dissertation, Kaiserslautern.

[9] Lasshof, B., 2005, Produktivität von Dienstleistungen, Dissertation, FernUniversität Hagen.

[10] Mont, O.K., 2000, Product-Service System, Swedish Environmental Protection Agency, Stockholm.

[11] Goedkoop, M.J., van Halen, C.J.G., te Riele, H.R.M., Rommens, P.J.M., 1999, Product Service Systems – Ecological and Economic Basics, PWC, The Hague. Journal of Cleaner Production, 14/17:1480-1494.

[12] Scheer, A.-W., 2001, ARIS: Vom Geschäftsprozess zum Anwendungssystem. Springer, Berlin.

11th Global Conference on Sustainable Manufacturing
– Innovative Solutions

The 2013 11th annual Global Conference on Sustainable Manufacturing (GCSM) sponsored by the International Academy for Production Engineering (CIRP) taking place in Technische Universität Berlin and Fraunhofer Production Technology Center is committed to exploiting the potentials of innovative technologies in economic, environmental and social dimensions for global value creation. If the lifestyles of upcoming and also developed communities will be shaped in the future by the existing, actually predominating technologies, then the resource consumption will exceed every accountable economic, environmental and social bound. The dynamics of global competition and cooperation shall be utilized for innovation and mediation towards the reasonably demanded sustainability on our globe. A special focus lies on condensing engineering to sustainable manufacturing, thus addressing artefact generation for shaping human living. The conference creates a platform for scientific and industrial exchange of ideas and will focus on the following areas:

- Value Creation by Sustainable Manufacturing
- Sustainability Assessment and Optimization
- Life Cycle Engineering and Assessment
- Product Design for Resource Efficiency and Effectiveness
- Manufacturing Process and Equipment
- Maintenance, Repair and Overhaul
- Remanufacturing, Reuse and Recycling
- Green Supply Chain and Transportation
- Information and Communication Technologies for Sustainability
- Innovative Energy Conversions
- Energy Efficiency
- Case Studies in Implementing various Aspects of Sustainable Manufacturing
- Water Resource Management for Sustainability
- Adequate Environments for Entrepreneurial Initiative
- Awareness for Sustainability in Public, Government and Economics